SwRI 5374-801

EMISSIONS MEASUREMENTS

- LOCOMOTIVES -

SwRI Project No. 08-5374-801
EPA Work Assignment 0-1
EPA Contract 68-C2-0144

Prepared For:

U.S. Environmental Protection Agency
2565 Plymouth Road
Ann Arbor, Michigan 48105

Prepared By:

Department of Emissions Research
Automotive Products and Emissions Research Division
Southwest Research Institute
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San Antonio, Texas 78228-0510

September 1993

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON
DETROIT WASHINGTON, DC

EPA 420/R-94-001

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September 1993

Approved:

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SUMMARY

This report was prepared for the National Vehicle and Fuel Emissions Laboratory of the Environmental Protection Agency by the Department of Emissions Research, Automotive Products and Emissions Research Division of Southwest Research Institute in response to Work Assignment 0-1 "Emissions Measurements - Locomotives" of EPA Contract 68-C2-0144. The Environmental Protection Agency (EPA) was directed in Section 213(a)(5) of the Clean Air Act (CAA), as amended in 1990, to promulgate emission standards applicable to locomotives and locomotive engines by December, 1995. This report attempts to identify procedures and sampling systems capable of simultaneous, accurate measurement of gaseous, particulate, smoke, and selected unregulated locomotive engine emissions. Evaluation criteria were developed to qualitatively address both the potential accuracy of a candidate sampling procedure or analytical method and its applicability to one or more of the potential operational scenarios being considered for locomotive engine testing. Suitable candidate procedures and methods have been identified and presented in the form of grouped lists of related candidates.

An evaluation of relevant information indicates that no existing sampling system or test procedure meets all of the established criteria. However, several locomotive emissions sampling options exist. Some are more feasible than others. Direct raw exhaust sampling is not viable for transient or pseudo-transient operation. However, raw exhaust sampling remains viable for steady-state gaseous and smoke emission measurements, but is not applicable to locomotive particulate emissions measurement. Particulate should be measured by diluting raw exhaust with a diluent (air) to closely duplicate real-world conditions and to be in line with the mobile source definition of particulate. For large engines (>600 hp), full flow exhaust dilution sampling procedures become impractical due to the need for very large (metered) quantities of dilution air. Split-then-dilute (splitter) systems offer viable alternatives to full-flow dilution techniques for measuring particulate emissions from locomotives operating at steady state.

EPA provided two conceptual sampling procedures for evaluation. Both concepts include mixing to ensure the homogeneity of the exhaust as it exits the locomotive stack, and then fractional sampling. The primary challenge with a fractional sampling approach is confirming the fraction of total exhaust flow. Simply relating cross-sectional area to volumetric flow has been shown to be an inadequate approach in experiments undertaken by Caterpillar. Much development work would be required before fractional sampling schemes could be considered viable for locomotive regulatory purposes.

Due to the growing interest and probable implementation (in non-attainment areas) of locomotives fueled with non-traditional fuels, Work Assignment 0-1 directed SwRI to evaluate test procedures suitable for measuring emissions from locomotives operating on various fuels. In an effort to account for the

effects of non-traditional fuels on emissions, the focus was placed primarily on the problems associated with measuring alcohol and aldehyde emissions. Procedures for measuring these (unregulated) emissions are well documented and may be easily implemented into most sampling scenarios given a representative sample.

The Work Assignment also stipulated that three engine operational scenarios be considered while developing the evaluation criteria and while evaluating candidate systems and methods (i.e., steady-state, step-change, and cyclic). All candidate sampling procedures and analytical methods identified were intended for use at steady state with the singular (non-viable) exception of 40 CFR Part 86 - Subpart N heavy-duty transient test procedures. Present locomotive emissions measurement procedures and techniques gather gaseous and particulate emissions data during equilibrated steady-state operating points; however, smoke emissions have been measured during both steady-state and cyclic operations. Some parameters can be measured in real time, while others cannot. Non-steady-state testing is complicated due to variable lag times between measurement events (as a function of sample system, locomotive type, ambient conditions, and test cycle, etc.) that require consideration to facilitate accurate mass emission calculations from emissions concentration data. Apparatus and test procedures for measuring gaseous and particulate emissions from locomotive engines do not currently possess the ability to test in non-steady-state engine operational scenarios. Simultaneous measurement of all engine and all emission parameters will remain very challenging, but is feasible for steady-state operation.

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LIST OF ABBREVIATIONS

CAA	Clean Air Act
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampler
ECE	United Nations Economic Commission for Europe
EEC	European Economic Community
EMA	MTU emissions measurement apparatus
EMD	Electro-Motive Division of General Motors Corporation
EPA	Environmental Protection Agency
°F	degrees Fahrenheit
GE	Transportation Systems Division of General Electric Company
HC	hydrocarbons
hp	horsepower
hr	hour
ISO	International Standards Organization
NMHC	non-methane hydrocarbons
NO_x	oxides of nitrogen
ORE	Office of Research and Experiments of the International Union of Railways
PDP	positive displacement pump
PM	particulate matter
psi	pounds per square inch
RIC	Reciprocating Internal Combustion
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
scf	standard cubic foot
SwRI	Southwest Research Institute

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FOREWORD

This project was performed for the National Vehicle and Fuel Emissions Laboratory of the Environmental Protection Agency by the Department of Emissions Research, Automotive Products and Emissions Research Division, Southwest Research Institute. The project was performed in response to Work Assignment 0-1 "Emissions Measurements - Locomotives," of EPA Contract 68-C2-0144. SwRI received Work Plan approval and began the technical effort on April 28, 1993. Work was completed on September 30, 1993.

The EPA Work Assignment Manager was Mr. Peter Hutchins and the Project Officer was Mr. Robert J. Johnson. Principal investigators for SwRI were Steven G. Fritz, Senior Research Engineer, and Michael E. Starr, Engineer, in the Department of Emissions Research. Dr. Lawrence R. Smith, Manager, Characterization and Chemical Analysis, was the SwRI Project Manager. Other SwRI management personnel were Mr. Terry L. Ullman, Manager, Heavy-Duty Control Methodology, and Mr. Charles T. Hare, Director, Department of Emissions Research.

I. OBJECTIVE OF WORK ASSIGNMENT

A. Statement of Work and Applicability of Study

The focus of this report was on the identification of potential exhaust emission test procedures and measurement systems that may be deemed appropriate for testing locomotives and locomotive engines. Analytical evaluations of candidate emissions sampling procedures and measurement systems are presented herein. Based on the outcome of the analytical evaluations, a test plan was prepared to further develop and verify a comprehensive test procedure and analysis package for measuring locomotive or locomotive engine emissions.

It was assumed that within the scope of this Work Assignment, locomotive engines were defined as the prime mover used for motive power in a locomotive. These engines are generally rated greater than 1000 hp. A locomotive is defined as a self-propelled piece of on-track railroad equipment as distinguishable from equipment designed for operation both on-track, and on-highway.

No regulations currently exist in the US which directly govern the testing of locomotive engine exhaust emissions. The Environmental Protection Agency (EPA) was directed in Section 213(a)(5) of the Clean Air Act (CAA), as amended in 1990, to promulgate emission standards applicable to locomotives and locomotive engines. The CAA directed the EPA to promulgate regulations by December, 1995.

Operation of locomotive engines has generally been considered to be represented by a discrete series of steady-state engine operating modes. To date, exhaust emissions from locomotives have been measured only under equilibrated steady-state operating conditions. There is an impetus by EPA to characterize emission magnitudes during locomotive mode switching (notch position changes) as well as during the subsequent stabilization time leading to equilibrium. Identification of in-use locomotive throttle operations and the accurate reproduction of those operations during measurement of locomotive engine emissions may be of importance to the investigation and eventual reduction of emissions from in-service locomotives. EPA has begun this investigation by working with the Association of American Railroads (AAR) and its member railroads to record in-use throttle events from selected trains.

The EPA contracted with Southwest Research Institute (SwRI) under Work Assignment No. 0-1 of Contract 68-C2-0144 to compile an anthology of sampling procedures and their associated analytical methods deemed applicable to testing locomotive exhaust emissions. Analytical methods and sampling procedures appropriate for testing locomotives operating on various alternative fuels, in addition to railroad diesel fuel, under various operating scenarios have been identified. Work Assignment 0-1 also included evaluation of sampling procedures using established criteria. A test plan was then proposed to further develop preferred sampling systems and analytical methods for measuring locomotive emissions.

B. Report Organization

This report presents EPA Work Assignment 0-1 Tasks 1.2, 1.3, and 1.4 in Sections II, III, and IV, respectively. Section II of this report simply lists locomotive engine emission measurement candidates, and completes Work Assignment Task 1.2. Candidate sampling procedures and analytical methods were identified and presented in logical groups comprised of similar and/or related candidates. Section III of this report presents results from an evaluation of those candidates, and completes Work Assignment Task 1.3. Although a clear distinction has been made between software and hardware candidates, the pertinent analytical procedures were appraised alongside related measurement devices due to the interdependency of such candidates. Options were outlined for resolving anticipated difficulties with some candidates; and procedures were suggested for demonstrating the accuracy of those options. Section IV of this report proposes a test plan for developing promising candidates, and completes Work Assignment Task 1.4. In an attempt to identify a comprehensive procedure and sampling system capable of simultaneous, accurate measurement of gaseous, particulate, smoke, and selected unregulated emissions, this report primarily focuses on diesel fueled locomotives performing any one of three distinct operating cycles. Complications or modifications anticipated with the use of alternative fuels were also addressed.

C. Summary of Task 1.1 - Criteria Report

Criteria were compiled in Task 1.1 of this Work Assignment to be used in evaluating candidate exhaust sampling procedures and analytical methods applicable to certification level locomotive emissions measurement. The Task 1.1 Final Report is included as Appendix A, which lists the evaluation criteria. Evaluation criteria were developed to qualitatively address both the potential accuracy of a candidate sampling procedure and the applicability of a given procedure to one or more of the potential operational scenarios being considered for locomotive engine testing. Discriminating elements were assigned to many criteria, in the form of brief discussions, for purposes of criterion weighting.

Suitability of measurement systems and sampling procedures for use with diesel as well as alternate fuels (e.g. "clean" diesel, bio-diesel (or mixtures thereof), natural gas, liquefied petroleum gas, alcohols (e.g. ethanol and methanol), or combinations of these fuels) was considered while drafting these criteria. Analytical procedures and sampling systems appropriate for testing emissions from locomotives operating on various fuels under various operating schemes have been identified and evaluated using these criteria.

Sampling systems and procedures are intended to be used for measurement of gaseous (hydrocarbons, carbon monoxide, carbon dioxide, oxides of nitrogen, alcohols, and aldehydes), particulate, and smoke emissions from a locomotive or locomotive engine. In conjunction with emission measurements, engine operational data (power, fuel rate, etc.) are also required to report emission results in brake specific terms. Evaluation criteria were established to identify procedures and sampling systems which would, ideally, permit measurement of all test parameters.

Due to procedural and systemic variability from one test system to the next, it was first necessary to categorize candidates according to their piecewise applicability within a total system, before applying criteria suitable for evaluation. The checklist shown in Table 1 was developed in Task 1.1. It will be used to begin characterizing the completeness of a candidate system with regard to locomotive emissions measurement potential.

Table 1. Checklist for Determining Applicable Criteria Groups

GROUP	INQUIRY	Y	N
A	Does the sampling system measure engine operating parameters?		
B	Does the design allow for timely particulate matter measurement?		
C	Does the design allow for timely gaseous emissions measurement?		
D	Does the design allow for timely smoke measurement?		
E	Does design allow for timely unregulated emissions measurement?		
F	Is simultaneous emissions measurement supported?		
G	Is steady-state testing supported?		
H	Are step-change tests (i.e.,transient range adjustments) supported?		
I	Are cycle tests (i.e.,rapid range & PM-filter changes) supported?		
J	Can all alternate fuels be tested without system modifications?		
K	Is calibration traceability provided with candidate system?		
L	Are all necessary components supplied with the candidate system?		
M	Can all candidate systems be serviced and calibrated by end user?		
N	Are there added provisions to ensure data completeness?		
O	Can computer software (included/required) be user customized?		

II. COMPILATION OF CANDIDATE SAMPLING SYSTEMS AND/OR ANALYTICAL PROCEDURES

Using technical literature searches and in-house experience, SwRI has identified exhaust sampling procedures for the measurement of gaseous (hydrocarbons, carbon monoxide, carbon dioxide, oxides of nitrogen, alcohols, and aldehydes), particulate, and smoke emissions that could be considered for use on a locomotive or locomotive engine. The candidate sampling procedures and analytical methods have been grouped according to specific applicability. SwRI has organized the candidate sampling procedures and analytical methods in preparation for appraisal of their ability to permit accurate simultaneous measurement of the above emissions.

It appears as though no one candidate shall be so complete as to have satisfied all sampling requirements. However, a comprehensive test procedure is envisioned which shall have satisfied as many as possible of the required elements, contain compatible components, and allow repeatable, calculable results of locomotive engine emissions. Such a composite system would consist of various candidate components and procedures which, when viewed separately, may not provide a complete "turn-key" system, but, in combination, form a comprehensive locomotive emissions testing procedure.

A. Discussion of Candidate Distinction

A clear distinction was made between "sampling procedure" and "analytical method" as candidates were being catalogued. Hardware devices and electronic instruments used for quantifying emissions were associated with computational methods deemed applicable for correctly reducing the acquired data. A comprehensive system which would permit accurate simultaneous measurement of locomotive or locomotive engine emissions presented an added dimension of difficulty, not easily managed by simply combining portions of one candidate with an other. Emphasis was placed on component compatibility, and pairing components with suitable analytical methods. Analytical methods had to be carefully matched to specific sampling systems, and generalizations were avoided.

B. Approach for Obtaining Representative Sample

The paramount task remains to identify, demonstrate, and incorporate a means by which to transfer a representative sample of locomotive engine exhaust into that comprehensive measurement system. Two suggested sampling procedures were developed by the EPA in an attempt to demonstrate a representative sample by means of fractional sampling techniques. Both theoretical designs contain mixing schemes which may extract a known portion of locomotive engine exhaust for introduction into the measurement system. Schemes or apparatuses aimed at providing a representative sample have been included as candidates, and this subject will be discussed in Section III of this report.

Candidate sampling procedures and analytical measurement methods presented below in Section II.C incorporate provisions for ensuring that a representative sample was drawn from the diesel engine exhaust (whether sampled raw or dilute). There are a number of conventional techniques for collecting a representative sample from heavy-duty truck sized diesel engines, however, this does not necessarily mean that such methods are applicable or even possible when testing locomotive engines.

C. Sampling Procedures and Analytical Measurement Methods

Task 1.2 of the Work Assignment required the identification of candidate exhaust sampling procedures and analytical measurement methods applicable to the measurement of locomotive exhaust. Suitable candidate procedures and methods have been identified and presented below in the form of grouped lists of related candidates. Individual subsections contain lists which were grouped according to specific testing needs.

The following subsections present candidate emissions sampling procedures and analytical methods for the measurement of gaseous, particulate, smoke, and selected unregulated emissions. Special emphasis has been placed on splitter systems (partial- or split-flow dilution) for particulate measurement. Also included were approaches to quantifying locomotive power, fuel flow, total exhaust flow and related engine operating parameters. Procedures were presented in order of their general use in the U.S. It should be reemphasized that Section II of this report was limited to the identification of candidates, and evaluations have been relegated to Section III.

1. Gaseous Emissions Measurement Candidates

Table 2 presents a listing of documented and commonly used candidate sampling procedures for gaseous emissions of HC, CO, CO_2, and NO_x. The instrumentation used for gaseous emissions measurement has been well documented, as have applicable raw gaseous emissions sampling systems. Concentrations of unburned hydrocarbons are expected to be measured using a heated flame ionization detector (HFID). Concentrations of carbon monoxide are expected to be measured using a nondispersive infrared analyzer (NDIR). Concentrations of carbon dioxide (required for fuel based calculations) are expected to be measured using another nondispersive infrared analyzer. Concentrations of oxides of nitrogen are expected to be measured using a chemiluminescent analyzer. It is important that a ice-bath water trap be used between the converter and the reaction chamber within the chemiluminiscent NO_x instrument to eliminate any vater vapor quenching effects.

Table 2. List of Gaseous Emission Measurement Procedures

A. 40 CFR Part 86, Subpart D "Emission Regulations for New Gasoline-Fueled and Diesel Heavy-Duty Engines: Gaseous Test Procedure." [4]

B. 40 CFR Part 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure." [5]

C. 40 CFR Part 89, Subpart D, "Control of Emission from New and In-Use Nonroad Compression-Ignition Engines at or Above 50 Horsepower -- Draft." [6]

D. SAE J177, "Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust." (Also see SAE J254, J215, J1003, J244) [3]

E. ISO 8178, Part 1, "RIC Engines - Exhaust Emission Measurement - Part 1: Test Bed Measurement of Gaseous and Particulates." [7]

F. ISO 8178, Part 2, "RIC Engines - Exhaust Emission Measurement - Part 2: At Site Measurement of Gaseous and Particulates." [8]

G. UN-ECE Regulation 49, "Uniform Provisions Concerning the Approval of Compression Ignition Engines and Vehicles With Regard to the Emissions of Pollutants by the Engine." [9]

H. AAR Draft Recommended Procedure for Measurement of Locomotive Engine Emissions [10]

I. International Union of Railways - Office of Research and Experiments (ORE), "Question S 1015P: Acceptance Testing of Diesel Engines -- Report Number 1 - Atmospheric Pollution Caused by Exhaust Fumes." [11]

2. Particulate Emissions Measurement Candidates

Table 3 presents a listing of documented candidate sampling procedures for the measurement of particulate emissions. Full-flow exhaust dilution is not expected to be practical for locomotive engine emissions testing; therefore, splitting off and then directing a known fraction of raw exhaust into a dilution system is expected to be a viable alternative. Such partial-flow dilution (splitter) methodologies are incorporated in candidate procedures for particulate measurement.

Table 3. List of Particulate Emission Measurement Procedures

A. 40 CFR Part 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure." [5]

B. ISO 8178, Part 1, "RIC Engines - Exhaust Emission Measurement - Part 1: Test Bed Measurement of Gaseous and Particulates." [7]

C. ISO 8178, Part 2, "RIC Engines - Exhaust Emission Measurement - Part 2: At Site Measurement of Gaseous and Particulates." [8]

D. UN-ECE Regulation 49, "Uniform Provisions Concerning the Approval of Compression Ignition Engines and Vehicles With Regard to the Emissions of Pollutants by the Engine." [9]

E. AAR Draft Recommended Procedure for Measurement of Locomotive Engine Emissions [10]

Suppliers of splitter systems are identified in Table 4. This list is not exhaustive from an international standpoint, but contains most systems that have either been used on locomotives in North America, or systems with which SwRI has become familiar. Note that all of these systems are intended only for steady-state measurement of particulate. Also note that the SwRI, EMD, and Ricardo systems have not been marketed commercially, and are used for "in-house" testing.

Table 4. Particulate Splitter Systems for Steady-State Measurements

A. SwRI 8-inch dilution tunnel system.

B. SwRI 6-inch portable dilution tunnel system.

C. Sierra Instruments "BGI Micro-Dilution Test Stand."

D. AVL "Smart Sampler."

E. AVL "Mini-Dilution Tunnel."

F. Ricardo splitter tunnel system.

G. EMD Splitter tunnel.

3. Candidate Alcohol and Aldehyde Emission Measurement Procedures

Measurement procedures and analytical methods for quantifying alcohol and aldehyde emissions are summarized in Table 5. Alcohol and aldehyde emissions from locomotives were of special interest due to the potential for locomotives to operate on non-traditional fuels (e.g., bio-diesel, natural gas, liquified petroleum gas, alcohols, or combinations or these fuels). Emissions of alcohols and/or aldehydes are expected to increase with the use of select alternative fuels.

Table 5. List of Alcohol and Aldehyde Emission Sampling Procedures

A. 40 CFR Part 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure," §1310-90 "Exhaust Gas Sampling and Analytical Systems for Petroleum Fueled and Methanol Fueled Diesel Engines." [5]

B. "Analytical Procedures for Characterizing Unregulated Emissions from Vehicles Using Middle-Distillate Fuels," EPA Interim Report No. EPA-600/2-80-068, (April 1980). [12]

C. "Characterization of Exhaust Emissions from Alcohol-Fueled Vehicles," SwRI Final Report No. 03-7670, Coordinating Research Council Report CAPE-30-81 (May 1985). [13]

D. SAE J1936 "Chemical Methods for the Measurement of Non-Regulated Diesel Emissions," (October 1989). [14]

E. SAE J1515 "Impact of Alternative Fuels on Engine Test and Reporting Procedures," (March 1988). [15]

4. Smoke Emissions Measurement Procedures and Sampling Systems

Smoke measurement procedures deemed applicable to measuring smoke emissions from diesel engines are presented in Table 6, and associated equipment and devices (smokemeters) are listed in Table 7. Smokemeters vary considerably in their principle of operation. The listing of smokemeters presented in Table 7 categorically distinguishes candidates by measurement principle.

Table 6. Listing of Smoke Emission Measurement Procedures

A Title 40, CFR, Part 86, Subpart I - Emission Regulations for New Diesel Heavy-Duty Engines; Smoke Exhaust Test Procedure. [16]

B. CARB "Snap-Idle" or free acceleration smoke test procedure [17]

C. ECE R24 "The Approval of CI Engines with Regard to the Emission of Visible Pollutants." (April 1986) [18]

D. ISO/TC22/SC5 Doc. N650 "Apparatus for the Measurement of the Opacity and for the Determination of the Light Absorption Coefficient of Exhaust Gas From Internal Combustion Engines" [19]

E. ISO 8178-3 "Smoke Measurement" -- Reciprocating Internal Combustion Engines - Measurement of Exhaust Emission - Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions. [20]

F. SAE J255a "Diesel Engine Smoke Measurement" [21]

g. SAE J35 "Diesel Smoke Measurement Procedure" [28]

Table 7. Listing of Smokemeters

Light Obscuring Smokemeters

A. U.S. Public Health Service (PHS) smokemeter.

B. Beckman smokemeter

C. Hartridge smokemeter

D. Wager smokemeter

E. McNab smokemeter

F. Celesco smokemeter

G. Thermoelectron

Light Dispersion Smokemeter

H. Robert Bosch Corporation

Filtering Methods

I. Bosch Spotmeter

Visual Methods

J. Ringelmann Rating

K. Photographic Scales - Film Strips

L. Reference Smoke Generators

Direct Soot Measurement

Photographic Methods

5. Test Procedures for Measurement of Engine Power, Fuel Flow, and Exhaust Gas Flow

In addition to sampling the locomotive engine exhaust, it is necessary to measure or compute exhaust gas volumetric flow rates for translating measured concentration data into mass flow rates of pollutants. Furthermore, it is likely that locomotive engine power output will have to be measured for normalizing the mass emission rate data into brake specific emissions, expressed in grams per brake horsepower hour (g/hp-hr). Based on SwRI's experience, developing a standardized test procedure for accurately determining the locomotive engine power output on varied locomotive engine models will be very challenging. This topic will be discussed in detail in Chapter 3 of this report. However, Table 8 presents several engine test procedures that are directly applicable to testing locomotive engines, or contain test procedures for testing diesel engines in general.

Table 8. Diesel Engine Test Procedures for Power, Fuel-Flow Rate, and Exhaust-Flow Rate

A. AAR / SwRI draft recommended procedure for measurement of locomotive engine emissions [10]

B. EMD locomotive field test procedures

C. GE locomotive field test procedures

D. AAR field test procedures [22,23]

E. UN-ECE Regulation 49, "Uniform Provisions Concerning the Approval of Compression Ignition Engines and Vehicles With Regard to the Emissions of Pollutants by the Engine." [9]

F. International Union of Railways - Office of Research and Experiments (ORE), "Question S 1015P: Acceptance Testing of Diesel Engines -- Report Number 1 - Atmospheric Pollution Caused by Exhaust Fumes." [11]

G. 40 CFR Part 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure," §1313-94 "Fuel Specifications." [5]

H. SAE J244 "Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines." [25]

I. SAE J1349 "Engine Power Test Code - Spark Ignited and Diesel" [26]

III. EVALUATION OF CANDIDATE SAMPLING SYSTEMS AND/OR ANALYTICAL PROCEDURES

A. Criteria Satisfied by Each Candidate Sampling System

Candidate sampling systems listed in the previous Section II of this report vary in their applicability for use in locomotive emissions measurement. Upon review of the evaluation criteria from the Task 1.1 report, it was readily apparent that no one system or procedure would meet all of the criteria. Therefore, the resultant locomotive exhaust emission test procedure will likely draw from various existing test procedures (as applicable), and new techniques and procedures may need to be developed and formalized.

Sections III.A.1 through III.A.10 present the significant test procedures which were considered to contain sampling procedures and analytical test methods relevant for locomotive use. Each procedure will be described in general terms, and particular emphasis will be placed on areas where SwRI believes that problems for its use with locomotives may be encountered. Analytical methods will be described in detail only when they deviate from EPA procedures or practices, and those differences make the procedure or method uniquely qualified for, or not applicable to locomotive testing. Options for resolving problem areas will be presented as appropriate.

Evaluations of procedures follow the criteria list shown earlier in Table 1, which was developed in Task 1.1. Recall that the Task 1.1 criteria report is included in its entirety as Appendix A. Detailed issues such as Groups K-O in the criteria are not included in the discussion below, but would become critical during the assessment of a complete procedure. See Appendix A for a more detailed description of the importance of Groups K-O.

1. 40 CFR Part 86 - Subpart D: 13-Mode Steady-State Gaseous Procedure

The test procedures and analytical methods in 40 CFR Part 86 - Subpart D "Emission Regulations for New Gasoline-Fueled and Diesel Heavy-Duty Engines; Gaseous Exhaust Test Procedure" are applicable for steady-state testing of locomotive exhaust emissions by sampling the raw, undiluted exhaust gas from the engine. Part 86 - Subpart D was the basis for developing the gaseous emissions procedures within the AAR recommended practice for locomotive exhaust emissions measurement described in Section III.A.7. [10] Presented below is a summary of the evaluation of Part 86 - Subpart D, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

Procedures for determining engine power output, fuel flow, and air flow rates are contained within Part 86 - Subpart D, but would have to be revised to take into account the scaling required for large engine testing, and the peculiarities involved with testing the engine in the vehicle application (i.e., within the locomotive). This topic is discussed in more detail in Section III.E of this report.

B. Does the design allow for timely particulate matter measurement? **No**

Particulate measurement is not included in Part 86 - Subpart D. However, particulate sampling techniques described in Section III.B are routinely used in conjunction with the steady-state gaseous sampling techniques in this procedure.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

D. Does the design allow for timely smoke measurement? **No**

Smoke measurement provisions are not included in Part 86 - Subpart D.

E. Does design allow for timely unregulated emissions measurement? **No**

Unregulated emission measurements are not covered in this procedure. However, conventional sampling techniques described later in Section III.C are routinely used in conjunction with the steady-state gaseous sampling techniques described in Subpart D.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure, however, other procedures for measuring particulate and smoke emissions could be used for simultaneous steady-state measurements.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from concentration data measured during step-changes have not been demonstrated using raw exhaust sampling in Subpart D. Though it should be technically feasible, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in gaseous emissions testing procedures are anticipated when testing alternative fuels. However, there are sample line length and temperature considerations while sampling for the presence of alcohol and aldehyde emissions. Natural gas fueled engines may require methane analyses. Note that Section III.-H of this report addresses special considerations for use with alternative fuels.

2. 40 CFR Part 86 - Subpart N: Heavy-Duty Diesel Engine Transient Testing

The test procedures and analytical methods in 40 CFR Part 86 - Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure" are applicable for transient testing of heavy-duty engines of roughly 100-500 hp. Dilute sampling of full flow exhaust is used for measuring gaseous and particulate emissions. Presented below is a summary of the evaluation of Part 86 - Subpart N, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

Procedures for determining heavy-duty engine power output, measured using a dynamometer, are contained within Part 86 - Subpart N. However, dilute sampling using a CVS system enables computation of mass emission rates without measuring fuel or air flow, and therefore, these are not addressed. Scaling of existing CVS systems designed for full flow exhaust testing of on-highway truck-sized engines in the 100-500 hp range up to a size necessary to test locomotives from 1000-5000 hp is generally not considered feasible.

B. Does the design allow for timely particulate matter measurement? **Yes**

Particulate measurement is included in Part 86 - Subpart N. Comments in Section III.A.2 (A) apply.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

Part 86 - Subpart N is intended for transient gaseous emission measurement, but is readily adaptable to steady-state measurements or measurements during a throttle notch step change. However,

D. Does the design allow for timely smoke measurement? **No**

Smoke measurement provisions are not included in Part 86 - Subpart N. A separate smoke test is used (40 CFR Part 86 - Subpart I.) [16]

E. Does design allow for timely unregulated emissions measurement? **Yes**

With the introduction of methanol fueled heavy-duty engines, Subpart N was updated to include provisions for sampling alcohols and aldehydes. Provisions for methane measurements from natural gas fueled engines have been proposed.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure. Subpart N covers regulated gaseous and particulate emissions. A separate smoke test procedure is used for certifying on-highway heavy-duty diesel engines.

G. Is steady-state testing supported? **Yes**

Although Subpart N is specifically designed for transient testing, steady-state testing using existing procedures and equipment is commonly performed as part of the engine development process. However, tunnel temperature problems are often encountered during high power steady-state testing in CVS systems sized for transient testing of such engines.

H. Are step-change tests (i.e.,transient range adjustments) supported? **Yes**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from measured concentration data measured during step-changes in locomotive engine operating conditions are covered using Subpart N. However, the scaling difficulties in CVS system design would remain.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **Yes**

Subpart N is designed for use in transient testing. However, the scaling problem described in Section III.A.2 (A) and later in Section III.G would remain.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in testing procedures are anticipated when testing alternative fuels. However, temperature and length of the sample transfer line to the dilution tunnel or sampling system, as well as increased dilution air flow requirements are constraints for alcohol fueled engine emission testing. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

3. 40 CFR Part 89 - Subpart D: Draft Non-Road Standards

The test procedures and analytical methods in 40 CFR Part 89 - Subpart D "Control of Emission from New and In-Use Nonroad Compression-Ignition Engines at or Above 50 Horsepower -- Draft" are applicable for steady-state testing of gaseous emissions from heavy-duty non-road diesel engines Raw or dilute sampling of full flow exhaust is used for measuring gaseous emissions. Presented below is a summary of the evaluation of Part 89 - Subpart D, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

As in Part 86 - Subpart D, procedures for determining engine power output, fuel flow, and air flow rates are contained within Part 89 - Subpart D, but would have to be revised to take into account the scaling required for large engine testing, and the peculiarities involved with testing the engine in the vehicle application (i.e.,within the locomotive). This topic will be discussed in more detail in Section 3.5 of this report.

B. Does the design allow for timely particulate matter measurement? **No**

Particulate measurement is not included in Part 89 - Subpart D.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

Part 89 - Subpart D is intended for steady-state gaseous emission measurement.

D. Does the design allow for timely smoke measurement? **No**

Smoke measurement provisions are not included in Part 89 - Subpart D. Part 89 refers to Part 86 - Subpart I for the smoke test procedure.

E. Does design allow for timely unregulated emissions measurement? **No**

Unregulated emission measurements are not covered in this procedure. However, conventional sampling techniques described later in Section 3.3 are routinely used in conjunction with the steady-state gaseous sampling techniques.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure, however, other procedures for measuring particulate and smoke emissions could be used for simultaneous steady-state measurements, without compromising this procedure.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from concentration data measured during step changes have not been demonstrated using raw exhaust sampling, in 40 CFR Part 89 - Subpart D. Though it should be technically feasible for gaseous emissions testing, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented, and particulate cannot be measured using a raw sample.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

4. SAE Recommended Practices: Steady-State Gaseous Procedure

The Society of Automotive Engineers (SAE) has a series of Recommended Practices that cover procedures and analytical methods for steady-state testing of gaseous emissions from diesel engines. SAE J1003 "Diesel Engine Emission Measurement Procedure"[24] is the governing procedure for steady-state testing of diesel engines, and references the following supporting SAE Procedures:

SAE J177	"Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust" [3]
SAE J215	"Continuous Hydrocarbon Analysis of Diesel Emissions" [1]
SAE J244	"Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines" [25]
SAE J1349	"Engine Power Test Code - Spark Ignited and Diesel" [26]
SAE J1243	"Diesel Emission Production Audit Test" [27]
SAE J255a	"Diesel Engine Smoke Measurement" [21]
SAE J35	"Diesel Smoke Measurement Procedure" [28]
SAE J1936	"Chemical Methods for the Measurement of Nonregulated Diesel Emissions" [14]
SAE J1151	"Methane Measurement Using Gas Chromatography" [29]

These procedures are substantially similar to 40 CFR Part 86 - Subparts D and I, wherein raw sampling techniques are used for measuring gaseous emissions, and a 13-mode steady-state weighting procedure is used to compute brake-specific emissions. Presented below is a summary of an evaluation of applicable SAE procedures, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

SAE J1003 is the governing procedure for steady-state testing of diesel engines. It covers the dynamometer test procedures, fuel specifications, instrumentation, test conditions, and test procedures. SAE J244 covers intake air flow or exhaust flow measurements necessary to compute mass emission rates from measured concentrations. The SAE procedures would have to be reviewed in detail to assess any scaling required for large engine testing, and the peculiarities involved with testing the engine in the vehicle application (i.e.,within the locomotive). This topic is discussed in more detail in Section 3.5 of this report.

B. Does the design allow for timely particulate matter measurement? **No**

Particulate measurement is not included in any SAE Recommended Procedures.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

The SAE procedures are only applicable for steady-state testing.

D. Does the design allow for timely smoke measurement? **Yes**

Smoke measurement provisions are included in SAE J255a, J1243, and J35. SAE J255a covers the general topic of diesel engine smoke measurement, including the nature of diesel smoke, how smoke can be measured, and how the various measurement methods can be correlated. SAE J35 is essentially the same as the Federal smoke test certification procedure in 40 CFR Part 86 - Subpart I. It covers the smoke test procedure, the test cycle, equipment and instrumentation, and data analyses. J1243 covers a production audit emission test which includes smoke opacity testing. Note that the test cycle in SAE J35 exercises the engine through operating regions that are not encountered with locomotives, and therefore is one area of the procedure that would require revision for use in locomotive testing. This issue will be discussed in additional detail in Section 3.4 of this report.

E. Does design allow for timely unregulated emissions measurement? **Yes**

SAE J1936 "Chemical Methods for the Measurement of Nonregulated Diesel Emissions" includes analytical procedures for the collection, analysis, and characterization of aldehydes, carbonyl compounds, sulfates, and the characterization of diesel particulates.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure. The steady-state gaseous test procedure is separate from the smoke test procedure. Particulate measurements are not included in the SAE procedures. However, other procedures for measuring particulate could be used simultaneously with steady-state gaseous measurements.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e., transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from concentration data measured during throttle notch step changes have not been demonstrated using raw exhaust sampling in the SAE procedures. Though it should be technically feasible for gaseous emissions, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

5. ISO 8178: Parts 1-7

The International Standards Organization (ISO) is developing a series of procedures and analytical methods for steady-state testing of gaseous, particulate, and smoke emissions from diesel engines. ISO 8178 "Reciprocating Internal Combustion Engines - Exhaust Emission Measurement" is the governing procedure for steady-state testing of reciprocating internal combustion (RIC) engines, and references seven Parts:

Part 1: "Test Bed Measurement of Gaseous and Particulate Exhaust Emission from RIC Engines"
Part 2: "At Site Measurement of Gaseous and Particulate Exhaust Emission from RIC Engines - Special Requirements for Using ISO 8178-1 at Site"
Part 3: "Definitions and Methods of Measurement of Exhaust Gas Smoke Under Steady-State Conditions"
Part 4: "Test Cycles for Different Engine Applications"
Part 5: "Specifications of Test Fuels"
Part 6: "Test Report"
Part 7: "Engine Family Concept"

The ISO 8178 procedures are not yet finalized. There are currently four working groups active in completing the 8178 procedures. Working Group 1 is elaborating on ISO 8178-2, at site measurements. Working Group 2 is addressing round robin testing. Working Group 3 is elaborating on 8178-5, test fuel specifications. Working Group 4 is addressing the engine family concept in 8178-7.

Presented below is a summary of the evaluation of applicable ISO 8178 procedures, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

ISO 8178-1 is the governing procedure for steady-state testing of diesel engines. It covers the dynamometer test procedures, test conditions, and test procedures. It also covers intake air flow or exhaust flow measurements necessary to compute mass emission rates from measured emission concentrations.

B. Does the design allow for timely particulate matter measurement? **Yes**

Steady-state particulate measurement is included in ISO 8178-1 and -2.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

D. Does the design allow for timely smoke measurement? **Yes**

Smoke measurement provisions are included in ISO 8178-3 for steady-state operation

E. Does design allow for timely unregulated emissions measurement? **No**

Alcohol and aldehyde measurements are not covered in ISO 8178.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure. The steady-state gaseous and particulate test procedure is distinct and separate from the smoke test procedure.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from measured concentration data measured during step-changes in engine operating conditions have not been demonstrated using raw exhaust sampling in the ISO 8178 procedure. Though it should be technically feasible for gaseous emissions, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

6. ECE Regulation No. 49: Steady-State Procedures

The United Nations Economic Commission for Europe (ECE) has a test procedure for steady-state testing of gaseous and particulate emissions from diesel engines, known as Regulation No. 49 (R49) "Uniform Provisions Concerning the Approval of Compression Ignition Engines and Vehicles With Regard to the Emissions of Pollutants by the Engine." A second procedure, known as Regulation No. 24 (R24) "The Approval of CI Engines with Regard to the Emission of Visible Pollutants," covers smoke from diesel engines. An evaluation of applicable ECE procedures, using established criteria, is presented below.

A. Does the sampling system measure engine operating parameters? **Yes**

ECE R49 covers the dynamometer test procedures, test conditions, and test procedures. It also covers intake air flow or exhaust flow measurements necessary to compute mass emission rates from measured concentrations. However, R49 would have to be revised to take into account the scaling required for large engine testing, and the peculiarities involved with testing the engine in the vehicle application (i.e.,within the locomotive). This topic is discussed in more detail in Section 3.5 of this report.

B. Does the design allow for timely particulate matter measurement? **Yes**

Steady-state particulate measurement is included in R49.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

D. Does the design allow for timely smoke measurement? **Yes**

Smoke measurement provisions are included in R24 for steady-state operation.

E. Does design allow for timely unregulated emissions measurement? **No**

Alcohol and aldehyde measurements are not covered in R49.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure. The steady-state gaseous and particulate test procedure is separate from the smoke test procedure.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from measured concentration data measured during step-changes in engine operating conditions have not been demonstrated using raw exhaust sampling in the R49 procedure. Though it should be technically feasible, SwRI is not aware of any documented instance where this has been done using raw gaseous sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

7. AAR Draft Recommended Procedure

The test procedures and analytical methods in the AAR "Draft Recommended Procedure for Measurement of Locomotive Engine Emissions," are applicable for steady-state testing of locomotive exhaust emissions by sampling raw, undiluted engine exhaust gas. In 1989, this procedure was developed by SwRI on behalf of the AAR in response to locomotive emission regulatory initiatives in California, and the recognized need by the railroad industry to come to consensus on emission measurement procedures. A technical review of the draft procedure was performed by EMD, GE, and Caterpillar. CFR Part 86 - Subpart D was the basis for developing the gaseous emissions procedures within the AAR recommended procedure. SwRI in-house experience with splitter-type particulate measurement systems was the basis for the implementation of a steady state particulate measurement technique. Smoke opacity measurements were not included in the draft AAR Recommended Procedure.

Note that it was the intent of the AAR procedure to be compatible with planned ISO 8178 test procedures. However, the AAR procedure was drafted in 1989, which coincided with ISO 8178 procedure development. Now that the ISO procedures have matured, a review of the final ISO procedures, as compared to the AAR recommended procedure, will be necessary to address conflicting methodologies. An evaluation of the AAR recommended procedure using established criteria is presented below.

A. Does the sampling system measure engine operating parameters? Yes

Procedures for determining engine power output, fuel-flow and air-flow rates are contained within the AAR procedure. Note, however, that the AAR procedure was developed with a focus on engine test bed measurements verses full locomotive measurements. Therefore, the AAR procedure will need revision to expand its scope to locomotive testing.

B. Does the design allow for timely particulate matter measurement? Yes

Steady-state particulate measurement is included in the AAR procedure. Particulate measurements are made using a splitter-type, PDP-CVS sampling system. Dilution ratio of the raw exhaust to diluted exhaust is determined via CO_2 concentration monitoring. The majority of the particulate emissions sampling system was taken from proven EPA procedures in 40 CFR Part 86 - Subpart N.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

Steady-state gaseous emissions are measured using EPA proven procedures, as per 40 CFR Part 86 - Subpart D.

D. Does the design allow for timely smoke measurement? **No**

Smoke measurement provisions are not included in the AAR procedure.

E. Does design allow for timely unregulated emissions measurement? **No**

Unregulated emission measurements are not covered in this procedure. However, conventional sampling techniques described later in Section 3.3 are routinely used in conjunction with the steady-state gaseous sampling techniques described by AAR.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure, however, other procedures for measuring particulate and smoke emissions could be used for simultaneous steady-state measurements, without compromising this procedure.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from emissions concentration data, measured during step changes to engine operating conditions, have not been demonstrated using raw exhaust sampling in the AAR procedure. Though it should be technically feasible for gaseous emissions, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in gaseous emissions testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

8. ORE Report 1: European Locomotive Test Procedure

The test procedures and analytical methods in the International Union of Railways, Office of Research and Experiments "Acceptance Testing of Diesel Engines: Report No. 1 - Atmospheric Pollution Caused by Exhaust Fumes," are expected to remain applicable for steady-state testing of locomotive exhaust emissions of CO, NO_x, HC, and SO_2 by sampling the raw, undiluted exhaust gas emitted from the engine. This procedure was last revised in October of 1991, and presented below is a summary of the evaluation of the ORE procedure, using established criteria.

A. Does the sampling system measure engine operating parameters? **Yes**

Procedures for determining engine power output and fuel flow rates are contained within the ORE procedure indirectly by referencing another ORE report, ORE B13/RP6 "Control and Calibration of Absorption Dynamometers for Measuring the Output Developed by the Engine Under Test."

B. Does the design allow for timely particulate matter measurement? **No**

Particulate measurement is not included in ORE R1.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

The ORE procedure is designed for steady-state gaseous emissions characterization. Three steady-state test modes were used:

(1) Idle (weighting = 60%)
(2) 60 percent of rated speed and 50 percent load (weighting = 15%)
(3) rated speed and load (weighting = 25%).

D. Does the design allow for timely smoke measurement? **Yes**

Steady-state smoke measurement is performed using a Bosch smokemeter at a single test point - 60 percent of rated engine speed, and 100 percent load. This operating condition is never experienced in U.S. locomotives, and in fact, may not be an achievable test point because of turbocharger surging problems.

E. Does design allow for timely unregulated emissions measurement? **No**

Unregulated emission measurements are not covered in this procedure.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure.

G. Is steady-state testing supported? **Yes**

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from concentration data measured during step-changes have not been demonstrated using raw exhaust sampling in ORE-R21. Though it should be technically feasible for gaseous emissions, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in gaseous emissions testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

9. Michigan Technological University Emissions Measurement Apparatus

A portable tailpipe emissions measurement apparatus (EMA), developed by Michigan Technological University for the U.S. Bureau of Mines, was identified by a contractor working for CARB in 1992 as a candidate system for measuring exhaust from locomotives. [30] This EMA was developed for identifying abnormal tailpipe emission concentrations from underground mining vehicles, and consists of an exhaust dilution system and a portable instrument package. [31] An evaluation of the Michigan Technological University EMA procedure, using established criteria, is presented below.

A. Does the sampling system measure engine operating parameters? **No**

The MTU-EMA system relies on look-up tables of engine volumetric efficiency for engine airflow, and on bsfc for fuel flow. It stalls the torque converter in the automatic transmission to load the vehicle engine. These approaches would clearly be unacceptable for certification testing.

B. Does the design allow for timely particulate matter measurement? **Yes**

The MTU-EMA dilutes diesel exhaust with compressed nitrogen or air at a predetermined dilution ratio, through a single pass filter. Typical sampling times were 30-60 seconds, with a 64mm diameter filter.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

The MTU-EMA was designed to measure the concentrations of CO, CO_2, NO, and NO_2 in the raw exhaust during steady-state conditions. Note that HC is not measured.

D. Does the design allow for timely smoke measurement? **No**

Smoke measurement provisions are not included in the MTU-EMA.

E. Does design allow for timely unregulated emissions measurement? **No**

Unregulated emission measurements are not covered in this procedure.

F. Is simultaneous emissions measurement supported? **No**

Simultaneous sampling of gaseous, particulate, and smoke emissions is not directly supported in this procedure, however, other procedures for measuring smoke emissions could be used for simultaneous steady-state measurements.

G. Is steady-state testing supported? **Yes**

Steady-state emissions are measured at a single operating point.

H. Are step-change tests (i.e.,transient range adjustments) supported? **No**

The sampling techniques, analytical methods, and calculations necessary to compute mass emission rates from concentration data measured during step-changes have not been demonstrated using raw exhaust sampling in the EMA procedure. Though it should be technically feasible for gaseous emissions, SwRI is not aware of any documented instance where this has been done using raw sampling.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **No**

As described above in (H), cyclic testing has not been documented.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in gaseous emissions testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

10. EPA Candidate Systems

In the Work Assignment, EPA indicated that they would provide one or two sampling procedures for inclusion in Task 1.3 for analytical evaluation. No attempt has been made to render schematic drawings for either of the two candidate mixing systems submitted to SwRI by the EPA for consideration and inclusion in this report. Rather, the verbatim descriptions of the two EPA candidate mixing systems were given in Appendix B. Visualization and rough sketches were used to determine that the general concepts within both of the EPA systems were abrupt mixing of the exhaust exiting the locomotive stack, and fractional sampling.

Both conceptual EPA proposed ideas would require more extensive design and fabrication efforts than any other suggested system, before a working prototype for locomotive testing could be realized. Their approach to mixing relies on colliding exhaust streams within a chamber, and then splitting total exhaust into "known" fractions based on cross-sectional area of ducts. The primary challenge with this fractional sampling approach is largely demonstrating the fraction of total exhaust flow. Simply relating cross-sectional area to volumetric flow has been shown to be an inadequate approach in experiments undertaken by Caterpillar. However, Mitsubishi documented related work in an SAE technical paper [36]. They reported reasonable success in correlating steady-state test results when comparing their fractional sampling system with full flow CVS data, and had less success with correlating transient test results. They assumed that raw exhaust gas entered the fractional sampler uniformly, and therefore relied on geometric area relationships to determine the volume of exhaust sampled, and that the temperature of the exhaust gas flowing through each fractional sampling tube was equal. Mitsubishi performed a number of experiments in an attempt to demonstrate the validity of these assumptions. A similar set of experiments would be required of any fractional system considered for locomotive engine testing.

Caterpillar abandoned an intricate approach using transducers (microphones) sensitive to minuscule changes in pressure that were used in an effort to tune a multi-duct fractional sampling device. Their system involved a mixing chamber and a multiplicity of orifices designed to each have the same upstream flow geometry. Although there was never a public disclosure of that apparatus, there was an internal presentation by Caterpillar describing said apparatus. The greatest challenge was found to be controlling pressure differential between orifices. An example of a problem found during prototype development was the use of sharp edged orifices for fractioning. Round-edged orifices were to be incorporated into later prototypes due to their higher flow coefficient. Efforts to improve flow calibration methods were eventually abandoned when it was realized that their final design yielded particulate emission results lower than a CVS-PDP system (which met EPA specifications) in parallel correlation testing. This may suggest (arguably) that fractional sampling systems which rely on elaborate sheet metal enclosures, have the effect of large mufflers, with great surface areas, and relative cool spots. Soluble organic matter could condense in such systems due to thermal gradients. Issues of obtaining a representative sample along with a brief discussion of thermophoresis are discussed further in Section 3.6 of this report. An evaluation of the EPA supplied mixing systems, using established criteria, is presented below.

A. Does the sampling system measure engine operating parameters? **No**

Engine power measurement is not addressed in the proposed EPA systems. If dilute fractional sampling is used, there would be no need to measure fuel flow or engine air flow. However, the need would remain to quantify engine power levels.

B. Does the design allow for timely particulate matter measurement? **Yes**

With dilute fractional sampling, particulates could be measured over steady-state or cyclic engine operation using proven EPA procedures in 40 CFR 86 - Subpart N for transient testing of heavy-duty diesel engines.

C. Does the design allow for timely gaseous emissions measurement? **Yes**

With dilute fractional sampling, gaseous emissions could be measured over steady-state or cyclic engine operation using proven EPA procedures in 40 CFR 86 - Subpart N for transient testing of heavy-duty diesel engines.

D. Does the design allow for timely smoke measurement? **No**

The details of smoke emission measurements are not covered in any detail within the proposed EPA systems. However, EPA has proposed that fractional sampling be used also for smoke measurements over the same operating conditions (steady-state or cyclic) as is used for gaseous and particulate emissions. One problem area is the interpretation of fractional sample smoke opacity data, and correlating such data with visible emissions from other engines.

E. Does design allow for timely unregulated emissions measurement? **Yes**

With dilute fractional sampling, unregulated gaseous emissions of alcohols and aldehydes could be measured over steady-state or cyclic engine operation using proven EPA procedures in 40 CFR 86 - Subpart N for transient testing of heavy-duty otto-cycle engines.

F. Is simultaneous emissions measurement supported? **Yes**

Simultaneous sampling of gaseous, particulate, and smoke emissions could be supported in this proposed procedure. Procedures would require extensive validation.

G. Is steady-state testing supported? **Yes**

However, the system would have to be designed to withstand relatively high, sustained operating temperatures encountered during extended high power operation.

H. Are step-change tests (i.e.,transient range adjustments) supported? **Yes**

Step-change emissions measurements should be possible with a successful fractional sampling technique, but only if a constantly proportioned volume of exhaust is split.

I. Are cycle tests (i.e.,rapid range & PM-filter changes) supported? **Yes**

As described above in (H), cyclic testing should be possible with fractional sampling.

J. Can all alternate fuels be tested without system modifications? **Yes**

No significant changes in gaseous emissions testing procedures are anticipated when testing alternative fuels. Note that Section III.H of this report addresses special considerations for use with alternative fuels.

11. Candidate Sampling System Attribute Summary

A summary of the candidate sampling system attributes is given in Table 9. Each of the candidate sampling procedures presented in the previous section of this report is listed with a generalized assessment of the procedures applicability to locomotive exhaust emission sampling criteria.

Table 9. Candidate Sampling System Attribute Summary

	Candidate Sampling System									
Question	A	B	C	D	E	F	G	H	I	J
1. Does the sampling procedure measure engine operating parameters?	●	●	●	●	●	●	●	●	○	○
2. Does the sampling procedure allow for timely particulate measurement?	○	●	○	○	●	●	●	○	●	●
3. Does the sampling procedure allow for timely gaseous emission measurement?	●	●	●	●	●	●	●	●	●	●
4. Does the sampling procedure allow for timely smoke opacity measurement?	○	○	○	●	●	●	○	●	○	⊖
5. Does the sampling procedure allow for timely unregulated emissions measurement?	⊖	●	⊖	●	⊖	⊖	⊖	⊖	○	⊖
6. Is simultaneous emissions measurement supported?	○	⊖	○	○	○	○	○	○	○	●
7. Is steady-state testing supported?	●	⊖	●	●	●	●	●	●	●	●
8. Are transient range adjustments (i.e. step-changes) supported?	○	●	○	○	○	○	○	○	○	●
9. Are cyclic tests supported?	○	●	○	○	○	○	○	○	○	●
10. Can all alternative fuels be tested without major system modification?	⊖	●	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖

Notes: ● = Yes - Procedure Generally Applicable
⊖ = Not addressed, but procedure could be adapted for locomotive testing
○ = Topic not addressed in sampling procedure

A = 40 CFR Part 86 - Subpart D: 13-Mode Steady-State Gaseous Procedure
B = 40 CFR Part 86 - Subpart N: Heavy-Duty Diesel Engine Transient Procedure
C = 40 CFR Part 89 - Subpart D: Draft Non-Road Diesel Engine Standards
D = SAE Recommended Practices: Steady-State Gaseous Procedures
E = ISO 8178: Parts 1-7
F = ECE Regulation No. 49: Steady-State Gaseous Procedures
G = AAR Draft Recommended Procedures
H = ORE Report No. 1: European Locomotive Test Procedure
I = Michigan Technological University Emissions Measurement Apparatus
J = EPA candidate systems (dilute fractional sampling)

B. Splitter-Type Particulate Measurement Systems

Measurement of particulate emissions from diesel locomotive engines poses significant challenges due to the relatively large exhaust flow rates from engines in this class. Full flow exhaust dilution sampling procedures become impractical due to the need for very large (metered) quantities of dilution air, for achieving a desired dilution ratio. Although a very limited amount of particulate emissions data exist for locomotive engines, several particulate measurement systems have been used, to varying extents, with limited success, for several years in steady-state locomotive emission testing applications. The basic principle of measurement is similar for each candidate particulate sampling system. A relatively small fraction of the total exhaust is removed from the stack and directed into some form of dilution tunnel. Cool, clean air (diluent) is combined with this "split" portion of raw exhaust in proportions ranging from approximately 5:1 to 20:1. Although candidate systems differ in configuration, there are some conventional splitter system parts, including the raw sample probe, transfer pipe, dilution tunnel, diluent conditioner, mixing chamber or orifice, (vacuum) pump, and sample filtration devices. Temperature and pressure sensors are common necessities for sample system monitoring with all candidate systems. The following subsections present related information for evaluating split-then-dilute particulate sampling techniques, before evaluating a group of candidate "splitter" systems that use this technique. Note that these sampling techniques have only been used in steady-state testing applications, and do not generally lend themselves to transient test usage.

1. Determining Split Exhaust Flow Dilution Factor

There are (at the most) two separate and distinct points where flow may be split into "known" fractions in these split-then-dilute sampling schemes. The first fractioning point occurs when a portion of the total raw exhaust is diverted (split) by a probe from the locomotive exhaust stack into a dilution tunnel (typically via a heated transfer pipe). The second fractioning point occurs after that raw (split) fraction of raw exhaust has been diluted.

After the first fractioning point, the raw exhaust is then mixed with a diluent of cool, clean ambient or compressed air. This splitting point introduces the added calculation found in partial-flow as compared with full-flow exhaust dilution analytical methods. Determining the dilution factor (ratio of diluent to split raw exhaust) in the dilution tunnel is perhaps the most critical parameter in computing particulate emission results using a split-then-dilute (partial-flow) sampling system. An accurate means for determining that fraction of raw exhaust which was split from the total raw exhaust is needed together with diluent air flow to accurately determine the particulate concentration in the raw exhaust, whether steady-state or transient. Several methods have been employed for tracking this ratio, or dilution factor, which are commonly one of three types: (general descriptions)

(1) The first method relies on volume measurements of diluent and dilute mixture, using (typically) large and cumbersome mechanical volumetric flow metering devices. After measuring both the dilute mixture flow and the diluent flow, the diluent was mathematically subtracted from the dilute mixture. The difference of these two relatively large numbers was declared as the amount of split exhaust drawn into the dilution tunnel.

(2) Similarly, smaller electronic mass flow metering devices have been used for indirectly tracking volumetric diluent and dilute flow rates for determining the dilution factor.

(3) In an effort to define the dilution factor, (arguably) more elegant techniques have been used to measure relative concentrations of a specific gaseous emissions constituent (CO_2 or NO_x) in the raw exhaust and in the dilute mixture within the dilution tunnel. With this method, the dilution ratio may be defined as the ratio of raw concentration to dilute concentration.

In these three methods, there remains the need to measure (or somehow quantify) total raw exhaust flow before mass emission rates can be computed from measured particulate concentration data. Total raw exhaust mass-flow rate is commonly computed either by adding the measured engine air-flow rate to the measured fuel-flow rate and assuming that all of the air and fuel were exhausted, or by relying on fuel flow rate measurements and performing a carbon balance.

Recall that the second fractioning point occurs after the raw (split) fraction of raw exhaust has been diluted. In many apparatuses, rather than filtering the entire dilute mixture, a portion of the dilute mixture is extracted from the tunnel and drawn through a filtering device. In such cases, precision is needed to determine the volume of dilute mixture drawn from the dilution tunnel through the filter media. Calibrated gas meters have been employed for measuring the volume of dilute mixture drawn through the filter(s). A range of dilute-mixture temperatures should be anticipated and simulated during gas meter calibration exercises. With a gas meter placed downstream of the filtering device, fouling of such a gas meter is to be expected (filter efficiencies only approach 97 percent), and regular gas meter validation is suggested to account for fouling effects. Mass flow devices may require similar calibration.

2. Particulate Definition

In general, dilution of diesel engine exhaust with cool, clean air is needed to simulate the phenomenon of a hot exhaust stream entering a cool (ambient) environment, and to maintain the particulate filter sample zone temperature at or below 125 °F to prevent the loss of volatile material at higher temperatures. This stage also serves to allow the particulate to agglomerate to a size more efficiently filtered while more closely duplicating real-world conditions. After exhaust has been diluted, a sample of the dilute mixture is extracted from the tunnel, and particulate is captured in preconditioned, weighed, (relatively efficient) filter media. For the purposes of this Work Assignment, SwRI has assumed that particulate emissions from locomotive engines were to be characterized in much the same manner as have particulate emissions from on-highway light-duty and heavy-duty vehicles in the U.S. (i.e., particulate is to be measured using comparable filter media, filter face velocity, and sample zone temperature). Any deviation from such proven and known sampling constraints would essentially redefine particulate, thus rendering comparison of emission results from this class of vehicle to any other class of vehicle or engine meaningless.

3. Limitations to Splitter-Type Sampling System Applicability

To determine the fraction of raw exhaust that had been split into a dilution tunnel, there have been several methods applied, with varied levels of success. However, due to the lack of real time dilution factor determination, no candidate system currently possesses the ability to monitor all conditions and react rapidly enough to be useful in anything but steady-state testing applications. Although real time dilution factor determination has not been substantiated using a candidate sampling procedure, had the ability to control and quantify the ratio of diluent to raw exhaust (entering the dilution tunnel) somehow been demonstrated, while simultaneously measuring total raw exhaust flow, there would remain the task of quantifying delays for each instrument and sample system component output. Such delays would be functions of engine operation, and these (lag time) corrections would have to be suitable for use in reckoning the occurrence of each measurement event to a specific test moment, for computing emission results. Therefore, non-steady-state modal locomotive particulate emissions analysis, using a splitter-type sampling system, is expected to remain a challenge and is not presently realized in a candidate system.

4. Candidate Splitter System Evaluation

Each of the candidate particulate sampling systems listed in Table 4 is intended for use only in steady-state test applications. To modify any one system for use in step change or cyclic test applications would require extensive redesign. The general assertion with the candidate splitter systems evaluated below, is that, for steady-state emissions testing, almost any one would seem to suffice. For anything but steady-state testing, there was not a single candidate that would prove viable.

A. The SwRI 8-inch dilution tunnel apparatus was designed and built by SwRI to be a portable split-then-dilute sampling system for particulate measurement. This dilution tunnel constitutes a PDP-CVS system. Exhaust is removed from the raw stack using a sample probe. The amount of raw exhaust extracted can be varied by controlling a valve mounted at the stack wall, between the sample probe and the heated transfer tube. The transfer tube is heated to prevent condensation. The valve is adjusted to allow as much raw exhaust as possible to enter the dilution tunnel, without exceeding the sample zone temperature of 125 °F. Diluent air is cleaned (filtered) and temperature controlled. In its present configuration, this sampling system has two parallel particulate filter holders, each containing a primary and backup filter (in series) for capturing particulate. Filter holders mount to dilution tunnel sampling probes using rapid connect and disconnect fittings. These holders were designed to house 90 mm diameter PTFE-coated glass-fiber filter media. Typical filter face sample flow velocity is 35 $\pm$ 5 cm/sec. Filter conditioning and weighing facilities, as well as calibration of each sampling system component, are performed at SwRI, by SwRI personnel, using NIST traceable calibration standards, as per 40 CFR Part 86, Subpart N. Determination of the dilution factor is facilitated both by mechanical flow measuring devices, and by comparing constituent gas (CO_2) concentration in the raw exhaust flow with that in the diluted flow. The use of these two techniques in parallel has provided a means for monitoring the (comparative) accuracy of each technique.

B. The SwRI 6-inch portable dilution tunnel system was designed and built by SwRI for use as a split-then-dilute sampling apparatus. This 6-inch diameter dilution tunnel system is very similar in principle to the SwRI 8-inch diameter dilution tunnel system described above. Major differences are that this system is more compact and self-contained, and relies solely on the comparison of constituent gas (CO_2) concentration in the raw exhaust flow and in the diluted flow to determine the dilution factor. Furthermore, unlike the horizontal orientation of the SwRI 8-inch tunnel, this 6-inch tunnel is mounted vertically, with dilute mixture flowing from top to bottom. Optional 20" by 20" filtration is supported with this system. Other than size (scaling), there are no notable sampling method differences between the two SwRI systems.

C. Sierra Instruments, Inc. commercially introduced an automated fractional sampling device labeled the "BGI Micro-Dilution Test Stand," which was made available in July, 1993. The overall package is very well presented, and appears to be quite compact and portable. No provision is included to measure anything other than those parameters associated with gathering a particulate sample. Several major differences exist between this system and all other candidate splitter systems. The similarities, however, include sample zone temperature guidelines, filter face velocity, and the usage of a primary and backup filter, as well as the filter media itself, all of which appear to conform to proposed ISO 8178-1 standards. The differences are in the means by which the dilution ratio is determined and an uncommon method for creating a dilute mixture in their unique "mixing chamber," plus the fact that the entire dilute mixture, as opposed to only a portion, is filtered for analyses.

Devices that measure mass flows are used for monitoring the dilution ratio, as compared to other methods that measure constituent gas concentrations. Documentation provided by Sierra indicates that the use of such mass flow measurement devices limits dilution ratio to 10:1, or less. A remotely controlled ball valve located at the exhaust stack wall, in-line between the sample probe and the mixing chamber, can be adjusted to alter the dilution ratio. A computer monitors devices used for measuring mass flow, but the system is not expected to permit direct validity checks or calibration in the field. The system is marketed only for steady-state particulate emissions measurement, and other inherent limitations (i.e., time-consuming filter changes with a single holder) are expected to preclude its use in non-steady-state engine operational scenarios.

The most significant dissimilarity with this splitter system is the innovative mixing chamber where dilution occurs. A small diameter (< 1 inch), porous walled, stainless-steel tube is used as the mixing chamber. Rather than merely inducing a mixture by combining and directing two streams (hot exhaust and cool air) down many tunnel diameters, the Sierra Instruments approach is to flow hot, raw exhaust through the center of a permeable-walled tube and force diluent (compressed air) at high pressure (90 psi) through that permeable wall, into the mixing chamber, in an effort to create a dilute mixture. Due to the absence of any transfer tube in this design, there may be problems when mounting this mixing apparatus directly onto a locomotive exhaust stack, as is recommended by Sierra Instruments. It is anticipated that excessive temperature and vibration problems would be serious concerns when mounting directly onto the stack.

Sierra Instruments purportedly has had reasonable success in correlating steady-state results obtained with this splitter system to results obtained with a full-flow dilution tunnel on truck size engines. Existing particulate sampling techniques using full-flow dilution tunnels follow EPA's procedure for transient emission testing of heavy-duty diesel engines. These full-flow dilution tunnels are often used for steady-state measurements, but because EPA has no test procedures or regulations for steady-state particulate emissions, one cannot state that correlation has been established with EPA techniques. Due to the novel dilution technique of the Sierra system, it may first be desirable to test locomotive exhaust in an attempt to correlate results with existing databases of locomotive particulate emission test results.

D. AVL LIST GmbH commercially introduced a dilution and particulate sampling system which they have labeled "Smart Sampler SPC 472." The Smart Sampler concept was first designed as a CVS secondary dilution tunnel in 1983, then later was adapted for use as a dilution system for raw exhaust. The AVL model SPC 472 sampling system retains the capacity to be used as a secondary dilution system and was modified to be used as a raw exhaust dilution system. No provision is included to measure anything other than those parameters associated with gathering a particulate sample.

This smart sampler is a partial flow dilution system that relies either on mass flow metering devices or on (optional) constituent gas (CO_2) concentration to determine and control the dilution ratio. A computer interconnects several measurement devices for system control, while sample flow and dilution rates are adjusted based on feedback from electronic mass flow metering devices. Calibration of these devices is performed automatically, using integral laminar flow elements. Veracity may not easily be checked by the operator. Automatic calibration involves the use of internal laminar flow elements, one of which is used to define the total dilute mixture flow rate. A second integral laminar flow element is used to define the split raw exhaust flow rate. Several dilution ratios are simulated in the calibration procedure, and the complete process is performed automatically.

In use, a sample probe is placed into the raw exhaust stream. A heated sample line then connects the probe to the inlet valve at the dilution tunnel entrance. The tunnel is 25 inches long and has a diameter of 1.5 inches. Diluent is supplied by a conditioned (compressed) air supply. The entire dilute mixture, as opposed to only a portion, is passed through a filter for analyses. There is a provision (optional) for multiple filter holders with this system.

AVL limits the use of this apparatus to steady-state testing. Real time determination of the mass flow rate of raw exhaust entering the tunnel is the primary obstacle to non-steady-state applications. Mass flow or volumetric based systems rely on the difference of two relatively large values (total tunnel flow minus diluent air flow) to define the amount of split exhaust drawn into the system. Fluctuating velocity of the raw exhaust gas flow can adversely affect the accuracy of mass flow based systems. Although implementation of the optional CO_2 based dilution factor control system is also expected to be limited to steady-state testing, the fact that the operator could regularly calibrate the gaseous instruments implies that drift problems (that may otherwise have gone unnoticed in a mass flow based system) could be traced. Furthermore, there is uncertainty as to how well an electronic mass flow metering device will perform under prolonged use.

E. AVL LIST GmbH commercially introduced a particulate sampling system labeled the "Mini-Dilution Tunnel MDT 474." No provision is included to measure anything other than those parameters associated with gathering a particulate sample. This system uses the principle of isokinetic sampling to regulate the split exhaust flow rate into the dilution tunnel. In general, isokinetic sampling implies that the velocity at which the raw exhaust is drawn (or split) into the sample probe is the same velocity at which the total raw exhaust is moving through the stack.

Measurement of the static pressure differential between sample probe and exhaust pipe yields a feedback (input parameter) to a control loop that operates a device for correcting mass flow rate in the heated transfer (split) pipe. Deemed a "pneumatic orifice," this device directs a regulated fraction of diluent in opposition to the flow of raw exhaust in the heated transfer pipe. This is done to reduce the split flow velocity in the transfer pipe to match that in the raw stack. Earlier designs altered the flow rate of total dilute mixture to achieve similar results. With this design, only the small fraction in the transfer pipe, and not the entire dilute flow, is monitored and regulated. Total dilute mixture flow rate is merely throttled to maintain the dilution tunnel pressure somewhat below that in the transfer pipe. Similar limitations apply to this (mass flow based) system that were stated for the AVL SPC 472 sampler.

An optional CO_2 measurement system was proposed by AVL to provide the control loop feedback. It would permit regulation of the split flow rate by measuring the CO_2 content of the exhaust gas in the dilution tunnel and in the split (raw) transfer pipe. The volumetric relationship between the split and the total raw exhaust flow may be calculated from the CO_2-concentration ratio in these two regions, if the total exhaust flow is known.

In use, clean (filtered) diluent is drawn, from an ambient source, into the MDT 474 dilution tunnel. Its diameter is 4 inches, and the effective length is 43 inches. Only a small portion of the dilute mixture is sampled for particulate, and a vacuum pump enables a constant portion of mass to flow from the tunnel through the particulate filters. where mass flow measurement is performed by a dry gas meter. The diameter of particulate filters supported by this system is 70 mm. One of three quick-connect filter holders (primary plus backup) may be selected for gathering the sample. This is done by switching a computer controlled array of electronic solenoids. This is advantageous in that several test points may be performed in succession without much time needed to exchange filter holders, but solenoid reliability (i.e., leakage) could become a problem that would be difficult to monitor. Increased tubular surface area, associated with the distance from dilution tunnel to filter media also appears to be an undesirable result of this feature.

Due to the inherent periodic pulsations in engine exhaust, the input to the differential pressure transducer, used by the isokinetic control loop, would have to be critically dampened. This system was designed to gather particulate during the performance of steady-state emission tests (i.e., ECE R49). Slow transient response with this system is not expected to accommodate (non-steady-state) fluctuations in exhaust flow. Test results obtained from steady-state sampling have shown deviations from CVS full-flow results by about 10 percent, with the MDT 474 system measuring higher levels in most cases. Due to this uncertainty, it would first be desirable to test locomotive exhaust using this apparatus, in an attempt to correlate results with the existing databases of locomotive particulate emission test results, before concluding this evaluation.

F. For large diesel engine testing, Ricardo Consulting Engineers has used an in-house "Mini Particulate Tunnel," which is a split-then-dilute sampling system. To vary the dilution ratio, a gate valve, located at the stack wall between the sample probe and the transfer pipe, is used to control the rate at which raw exhaust is split into the dilution tunnel. As the dilution ratio varies, that split amount is calculated, as with similar (CO_2 based) systems, using the ratio of a constituent gas (NO_x) concentration in the raw and dilute flows to define the dilution factor. The principle of operation for this particulate sampling device and that of the SwRI 6-inch Mini Tunnel described above are substantially similar. However, limited information for the Ricardo device shows no diluent conditioning other than simple filtration. The ambient air temperature, in the vicinity of a locomotive exhaust stack, is expected to require artificial cooling at most emission test sites.

G. General Motors Research (GMR) Laboratories attempted to develop a splitter tunnel for use in characterizing effects of dilution ratio and filter temperature on diesel exhaust particulate. The methodology that went along with that system was described in an SAE report. [32] That system was later used at EMD for particulate measurement of locomotive engines. Due to manpower limitations and gaseous exhaust emission test requirements taking precedence, a limited amount of time and funds were allocated by EMD to adapt that (automotive) system to diesel locomotive applications. The dilution tunnel had a 60 mm diameter, which depended largely on a converging and diverging dilution nozzle to create a localized low pressure region for drawing raw exhaust into the system. Samples collected from the center of that dilution tunnel were shown to have been representative samples. The filter media used were 45 mm diameter glass fiber disks. Dilution ratio was determined by relating a specific constituent gas (CO_2) concentration in the raw exhaust stack to that measured in the dilute flow. The only application of this system was in light-duty steady-state testing, and EMD has not completely adapted this system for locomotive testing applications. Responses to a questionnaire that requested details about this system were provided by EMD, and are included in this report as Appendix C.

C. Alcohol and Aldehyde Measurement Procedures

Due to the growing interest and probable implementation (in non-attainment areas) of locomotives fueled with non-traditional fuels (e.g., natural gas), Work Assignment 0-1 directed SwRI to evaluate test procedures suitable for measuring emissions from locomotives operating on various fuels. It is favorable to eventually promulgate regulations that do not require major modifications to accommodate the use of specific fuels. In an effort to account for the effects of non-traditional fuels on emissions, the focus was expected to be placed primarily on the monitoring of alcohol and aldehyde emissions. It is anticipated that procedures listed in Table 5 will not require more than minor modifications prior to being deemed applicable to sampling locomotive exhaust.

Sampling procedures and analytical methods for sampling exhaust emissions for the presence of alcohols or aldehydes have evolved over the past several years into the comprehensive procedure listed in the CFR. Without notable exception, the scientific content of SAE J1936 [14], SAE J1515 [33], as well as procedures outlined by SwRI in 1980 and 1985 [12,13], were largely incorporated during development of 40 CFR Part 86, Subpart N. [5] Steady-state testing is supported, and step-change testing could be performed if cumulative or composite cycle average emission results would suffice. Conducting the tests substantially as outlined in the CFR would not hinder simultaneous measurement of other emissions, provided sample probe interference could be avoided.

D. Smoke Test Procedures

Locomotive exhaust smoke measurement procedures are defined for use in screening the existing locomotive fleet for "excessive" smoke. However, current practices of visual- and opacity-based smoke measurement procedures are likely to be found inadequate for certification level testing purposes.

Within the last 5 years, a renewed interest in locomotive smoke measurement has occurred due to the aggressive enforcement of visible emission regulations as applied to locomotives operating in the South Coast Air Quality Management District (SCAQMD) of California. SCAQMD Rule 401 (attached as Appendix D) uses Ringelmann Chart visual observations by certified inspectors to limit smoke emissions below Ringelmann 1. The California Air Resources Board (CARB) Rule 41701 (attached as Appendix E) limits smoke emissions to Ringelmann 2. Railroads operating in the SCAQMD are very familiar with the Ringelmann visual rating system, and have personnel certified to monitor their fleets.

As a result of the SCAQMD enforcement, the three major California freight railroads have also implemented smoke opacity measurement at selected maintenance sites. Wager smokemeters have been commonly used for these measurements. Although no universal test procedures exist, steady-state smoke is typically recorded at each throttle notch position on a fully warmed engine.

Electronic smoke opacity measurements using light extinction based smokemeters is a mature technology. The equipment and analytical procedures detailed in 40 CFR Part 86 - Subpart I for heavy-duty diesel engines (the Federal Smoke Test) [16], in ISO 8178-3 [20], and the ECE R24 [18] could be applicable for locomotives.

The primary debate is over what operating conditions smoke opacity is to be measured, and how the measured opacity data shall be interpreted. The current practice used for reporting opacity to the SCAQMD is to measure and report the stabilized steady-state smoke opacity (reported in percent opacity) at each throttle notch (idle through Notch 8) on a fully warmed locomotive engine. The sampling points and the interpretation of the opacity data in this approach is well defined, and very straight forward.

A problem would arise in smoke opacity data interpretation if test protocol were to attempt to include non steady-state smoke measurements. Although it is generally recognized that smoke opacity increases momentarily above steady-state levels during throttle notch changes, the smoke opacity during these events is easily recorded. However, translation of the recorded smoke trace into a standard format is needed together with an accepted definition of the standard.

Major issues in developing a smoke standard will likely be:

1. How to handle multiple stack locomotives? Although most turbocharged locomotives have a single exhaust stack, roots-blown EMD locomotives often have two exhaust stacks.

2. How to address different exhaust stack sizes? The optical path length of the smoke opacity measurement changes with the subtle differences that exist in locomotive exhaust stack sizes. ISO 8178-3 addresses this issue by defining a "light absorption coefficient" that effectively normalizes smoke measurements over various optical path lengths. This type of "smoke density" standard may be preferred over an opacity-based standard.

3. Over what operating scenarios and ambient conditions are smoke measurements to be made and reported? Steady-state or transient? If transient, over selected step-change throttle operations, or over some operating cycle?

4. If non stabilized, non-steady-state smoke opacity measurements are used, the interpretation of the instantaneous smoke opacity measurements remains suspect.

5. Will opacity-based certification smoke standards and test procedures that are used for in-use monitoring purposes supersede and/or override current visual based local regulations?

6. Will it be necessary to shield smoke opacity meters installed on locomotives from the effects of wind?

E. Measurement of Power, Fuel Flow, and Exhaust Flow Rate

Assuming that locomotive rulemaking will be specified on a brake specific basis (grams per brake horsepower hour, g/hp-hr), an accurate means for quantifying engine power will be needed. Each of the locomotive engine builders, and most railroad companies, have detailed procedures for measuring power and diesel fuel consumption rates. The existing procedures used by the railroads typically yield very accurate results, with target accuracies in fuel consumption tests on the order of one-quarter to one-half of one percent. Of concern to an emissions measuring facility is that each of the engine builders and railroad companies performs measurement tasks in differing manners. If the EPA were to gather several of these (different) methods and consolidate them into one acceptable procedure for quantifying (diesel) fuel consumption and locomotive engine power output, then uniformity could be realized. Although it was outside of the scope of this project, this is not considered to be an immense task, it simply has not been undertaken by any one, to date. Specific areas of concern (i.e., needing a calibrated shunt, accessory loads, handling head end power (HEP) on passenger locomotives, and correcting to flywheel, etc.) may be addressed while consolidating those existing procedures. Note that these procedures are for measuring fuel and power only with an engine operating at steady state. Also note that the consumption rate of natural gas and/or other alternative fuels is not expected to be easily measured using conventional methods, and may not be addressed in those in-house procedures. Dual fuel (diesel and natural gas) currently under development further complicate this issue.

If full-flow dilution or fractional sampling techniques could be effectively implemented, the need for exhaust flow measurement would diminish. However, the more likely eventuality is that exhaust flow rate will indeed be required together with steady-state emission measurements for completing the mass emission rate calculations from the gathered emissions concentration data. Several means are in active use for determining the exhaust flow rate from in-use locomotive engines. If the mass flow rate of fuel can be accurately determined, then a computed fuel-to-air ratio can be used to compute inlet air flow. Using that method, air flow plus fuel flow equals total exhaust flow rate. Notwithstanding the relatively large volumetric air flow rate of a locomotive engine at higher power output modes, it has been shown that air flow measurement can be performed by monitoring the pressure drop across a calibrated flow meter. This technique is less difficult in a laboratory test site than on an in-use locomotive. Access to the engine air intake of a locomotive is restricted. and the increased inlet restriction would introduce a new variable. If air flow and fuel flow can be measured, then total exhaust flow can be deduced as the sum of these two values. Furthermore, the measured fuel-to-air ratio can be used to compare with the theoretical fuel-to-air ratio described above. Close agreement between the two F/A-ratio methods indicates the integrity of the (representative) sample. It should be noted that these procedures are only for use in steady-state operations.

F. Obtaining a Representative Exhaust Sample for Analyses

Due to the relatively large volumetric flow rate of locomotive engine exhaust, even during moderate power output, it was not expected to be practical to sample (or dilute) the entire exhaust stream. Rather, a representative portion of the exhaust should be obtained and analyzed. This is not a new concept in gaseous emissions measurement. Extracting a representative sample of diesel engine exhaust has been routinely performed, and the techniques for doing so are well documented.

For particulate sampling, there are two points at which a representative sample should exist when applying split-then-dilute sampling techniques: first, at the location in the raw stack where the portion of raw exhaust is split or diverted into the dilution tunnel; and second, at the location in the dilution tunnel where dilute sampling occurs. Obtaining a representative sample presupposes that the host mixture be homogeneous. Arguably, the exhaust from a turbocharged locomotive exits the stack thoroughly mixed, requiring only a relatively short stack extension on which to mount various probes for drawing homogeneous samples. However, the tunnel into which the exhaust is directed for dilution should be of sufficient length to induce mixing.

For both raw exhaust and/or dilution tunnel sampling, other considerations include the configuration of the sample probe, and (with dilution tunnels) the mixing orifice. Sample probe location is largely dictated by a distance downstream of the entrance: typically the probe is placed 8 to 10 tunnel diameters downstream of a tunnel or stack entrance. Several additional pipe diameters are included past the probe to allow for undisturbed flow, well beyond the probe. In a laboratory, it may be feasible to construct an exhaust pipe or tunnel from which a portion of raw locomotive exhaust may be removed for analyses, but field testing of locomotive engine emissions is expected to present problems with regard to tunnel fabrication. Exhaust stack(s) are of varied dimensions from one locomotive to an other, and multiple stack locomotives further compound the problem (non-turbocharged locomotive engines often have more than one exhaust stack). The following subsections introduce concerns, provide discussion, and suggest related sampling issues.

1. Handling Variations in Exhaust Continuity

Other considerations related to, but distinct from, the representative sample itself are spatial and temporal variations in the observed exhaust composition. An example of spatial variation would be a nonuniform exhaust-flow profile in the exhaust system. Generally, for smaller engine applications, it has been assumed that thoughtful probe design will anticipate and address non-uniformly distributed flow profiles. Similar assumptions may be made for locomotive exhaust sampling; however, the need for an extended exhaust stack system is uncertain with an engine operating at steady-state. An example of temporal variation is an occasional puff of smoke emitted from the exhaust system. Wisps of visible smoke, typical of a diesel engine fuel injection system not operating ideally, may be managed by simply measuring and recording the emissions instrument signal over a brief time and averaging (integrating) momentary fluctuations in exhaust concentration. Emissions instrument sampling range and sample system transient response are expected to limit the use of such techniques for anything but steady-state testing.

2. Sample Probe Configuration

For the procedures evaluated, probe design for both raw and dilute sampling systems has generally been limited to one of two types. The first type is the pitot tube style of probe placed along the centerline of the tunnel, with the open-tip entrance in line with the exhaust flow. The ratio of tunnel diameter to tube diameter places a limit on probe size: the lower limit is typically 4:1. The second style of probe relies on a tube with a series of drilled holes to capture the sample. Holes should be sized similarly to allow uniform sample capture along the probe length. The probe is placed normal to the exhaust flow across the stack or tunnel diameter. To prevent exhaust from passing directly through this type of probe, hole patterns typically do not allow the placement of any two holes on the same plane to be 180 $\pm$ 20 degrees. Tube diameter is similar to, and limited by, the attached sample line which usually has a diameter less than one half inch. 40 CFR Part 86, Subpart D contains related information which, without exception, is reflective of all applicable candidate procedures on the subject of probe design. [4]

3. Approach to Verifying Representative Sample

Methods for determining the extent to which a portion of exhaust is representative of the whole are already well documented. Locomotive engine emissions testing is likely to require the use of one or more such verification techniques for demonstrating the presence of a representative sample. Carbon balance fuel consumption determination is a technique that is widely accepted, which lends itself to locomotive testing applications. If accurate measurements of fuel and air flow are available, then a means for verifying the representative nature of the exhaust sample is to compare measured fuel-to-air ratio with a computed fuel-to-air ratio (based on emission measurements). If these two ratios agree to within a specified percentage, then it may be deduced that the mixture was indeed representative (e.g., 40 CFR §86.345-79 requires that the two ratios agree to within 10 percent; however, idle and 2 percent modes do not have to meet this requirement). This procedure is routinely used at SwRI's locomotive engine laboratory for validation of a representative emissions sample. This technique has also been successfully used by SwRI in field testing of locomotives.

If there is need for further verification of a representative sample, there are procedures which inject a metered quantity of a "tracer" gas into the exhaust system (not through combustion). The concentration of the tracer gas in the dilution tunnel discharge is compared to that injected, for verification of representative sample in a dilution system. Sulfurhexafluoride (SF_6) is an example of a tracer gas that has been used for this technique. There are shortcomings to this technique. For example, unless the tracer gas is injected into a system with exhaust (i.e., at emission testing temperature), artificial exhaust system heating may be needed. Otherwise, results may not be indicative of what would be observed had the procedure been conducted at the higher operating temperature. Furthermore, a range of new variables would be introduced (i.e., mass flow detector and tracer gas instrument calibration, tracer gas cylinder leakage).

4. Additional Sampling Concerns

Preconditioning of an exhaust system is expected to be crucial to accurate particulate measurement. Although sufficient flow and good mixing should eliminate such problems, elaborate schemes which specify a fabricated mixing chamber are likely to encounter problems with thermal adhesion (thermophoresis). Thermophoretic forces tend to drive particles down the temperature gradient from hot to cool surfaces. [34] Clearly, particle deposition by thermophoresis will be an important consideration in the evaluation of exhaust sampling systems, but the real concern will be the potential for wall deposits to loosen and become reentrained in an unpredictable manner under test conditions. Problems with particle adhesion notwithstanding, the methods given above are expected to be directly applied to, or modified to permit, locomotive engine emissions testing. Drawing a portion of exhaust from the stack of a locomotive engine can be performed much like removing a sample from a heavy-duty CVS dilution system. However, with particulate measurement, it would then be necessary to dilute that "split" portion of exhaust with a clean diluent (air) to comply with an anticipated sample zone temperature limitation of 125 °F.

G. Sensitivity to Locomotive Operating Cycle

The Work Assignment stipulated that three locomotive or locomotive engine operational scenarios be considered while developing the evaluation criteria and while evaluating candidate systems and methods. The three engine operational scenarios are elaborated upon, in the following subsections.

1. Steady-State Operation

If exhaust emission measurements are performed only at discrete throttle notch positions, after sufficient time has passed to allow equilibration, the evaluation of sampling procedures and analytical methods, using established criteria, indicates that such measurements of steady-state locomotive emissions may be made without major modifications to existing sampling procedures and analytical methods.

2. Non-Steady-State (Pseudo-Transient) Operation

Non-steady-state or pseudo-transient operation was defined in the Work Assignment as the initiation of data collection at the moment the throttle is moved from one notch position to an other, and continuing for a specified period of time. A supplemental measurement could be performed following a prescribed stabilization period, and the stabilization time may not necessarily be the same for each throttle notch position tested. Measurement of raw gaseous emissions from a locomotive engine performing such a (pseudo-transient) operation may be feasible. However, computing mass emission rates from measured emission concentration data is difficult due to the absence of real-time air-flow or fuel-flow data. In addition, due to the absence of a viable means for determining the dilution ratio in real time, particulate measurement is expected to be limited to an accumulation gathered at dilution ratios that are, at best, questionable, throughout the duration of each such test (i.e., of little scientific use).

If each constituent gas analyzer range could provide useful data from the minimum to the maximum concentration excursion during such a test, without exceeding some boundaries established between the zero and span points, then the concentrations (instrument signals) may be recorded or integrated over that period of time between notches leading to equilibrium. Operating a gaseous analyzer at either extreme is generally not advisable due to increased relative error. The difficulty with changing analyzer ranges during a test, when using only one analyzer for measuring each constituent gas, even with the newer (so-called) automatic-spanning instruments, stems from the unpredictable amount of time required to do so. If computed mass emission rates or brake specific, real time emission results are desired, knowledge of the inherent delay of each analyzer's output would be required. Similarly, dilution ratio methodologies for particulate measurements, that are reliant upon the ratio of constituent gas (CO_2 or NO_x) concentrations, also would require successful resolution of this (lag-time) issue before a real time dilution ratio could be realized using those methods with locomotives. A procedure for investigating instrument response is detailed in 40 CFR Part 86, Subpart D (§86.329). Furthermore, as an example, the chemiluminescent analyzers used for measuring concentrations of NO_x do not respond as rapidly as, say, an NDIR analyzer used for measuring CO and/or CO_2. It would not be uncommon for such an (NO_x) instrument to require twenty seconds to register the appropriate signal. Lengthy sample lines and flow rate limitations would only add to the delayed response. Such lag times may be difficult to define without thorough and extensive investigation of an in-use raw gaseous emissions sampling system.

3. Cyclic Operation

Cyclic operation was defined in the Work Assignment as operating the locomotive or locomotive engine over a prescribed sequence of throttle notch positions while a single composite exhaust gas and particulate sample is collected. Exhaust smoke would be measured continuously. Commentary from Section III.G.2 also applies to cyclic operation.

If instrument output could be accurately recorded, and perhaps integrated, smoke measurement would be possible throughout this type of cyclic test, as may raw gaseous emissions measurement, but split-then-dilute particulate measurement techniques are not currently viable. Even a composite particulate sample would require real time dilution factor determination for inclusion with instrument signals, but candidate splitter systems are presently deficient in this regard.

H. Special Considerations for Use With Alternative Fuels

As stated in Section III.E, the consumption rate of natural gas and/or other alternative fuels is not expected to be easily measured using conventional methods, and may not be addressed in the in-house procedures of present day engine manufacturers and railroad companies. If the rate of flow into the engine's fuel system could somehow be quantified, there remains the need to measure the flow of fuel being returned to the tank, to define total actual consumption. Generally there are only invasive methods for physically measuring fuel flow, such as installing a tee into a fuel line for a metering device. The entire issue of measuring fuel flow is complicated by the introduction of dual-fuel locomotives. Such engines are under development (i.e., diesel pilot ignited natural gas fueled locomotives), which start and idle on 100% diesel but run on a mixture of natural gas and diesel at higher power output modes. Determining a hydrogen to carbon ratio (HCR) for such an application becomes increasingly more difficult, as fuel compositions vary. HCR is needed to complete carbon balance based fuel rate calculations and related emissions data reduction.

For fractional sampling and with PDP-CVS schemes, there is a need to increase the diluent (air) flow rate in the dilution system when testing engines operating on methanol or natural gas fueled locomotives. Higher contents of water in the engine exhaust may be reduced by increasing the temperature and flow rate of diluent, using proven (documented) engineering practices. 40 CFR Part 86, Subpart N (§86.1309-90 (6)(b)(4)) outlines the requirements with which a PDP-CVS shall conform, by citing EPA 460/3-83-009. [35]

The response of a hydrocarbon analyzer to methane is a concern for natural gas fueled engines. Methane response factors on natural gas fueled engines need to be understood. There needs to be a procedure specified for use with nondispersive infrared type hydrocarbon analyzers calibrated on methane/propane. If there is to be a non-methane hydrocarbon (NMHC) standard for inclusion when testing natural gas fueled engines, there needs to be a methane sampling procedure specified.

I. Potential for Simultaneous Sampling of Gaseous, Particulate, and Smoke Emissions

Present locomotive testing practice is to sample gaseous and particulate emissions simultaneously, with a separate smoke test. This is not unlike the present approach to testing heavy-duty on-highway vehicle emissions. A laboratory mounted locomotive engine could be a candidate for complete simultaneous measurement of gaseous, particulate, and smoke emissions. However, it should be stipulated that the placement of any in-line smokemeter should be downstream of the gaseous and particulate sampling probes. This is due to the function of such smokemeters. They typically utilize a burst of air to keep the instrument lenses clean, and that air could inadvertently dilute exhaust entering sample probes if placed upstream. Note that the problem with removing samples from the raw stack of a locomotive for gaseous and/or particulate analyses is that the smoke measurement would likely be influenced. Levels of smoke would be reduced as portions of the total flow are diverted prior to the smokemeter.

Fractional sampling techniques could (conceptually) perform simultaneous sampling of gaseous, particulate, and smoke emissions. A note to consider with the fractional sampling approach is that if a fraction of the total exhaust is used for measuring smoke opacity, then what does that provide in the way of useful information? Is there any means for converting such values into what would have been measured had the total flow of exhaust undergone opacity analysis? Answers to these questions are beyond the scope of this report, however, it can be stated that fractional sampling techniques are not expected to be applicable beyond steady-state test usage, and the complexity of a (viable) system of this type may outweigh its potential gains.

IV. DEVELOPMENT AND VERIFICATION

The objective of Task 1.4 of Work Assignment 0-1 was to prepare a test plan to develop and verify locomotive exhaust emission sampling procedures. Although an evaluation of relevant information indicates that no sampling system or test procedure meets all of the established criteria, several sampling options exist for measuring locomotive emissions, and some are more feasible than others.

Given the sampling procedures and analytical methods evaluated in Section III of this report, a decision in principle (arguably) needs to be made as to which of the two following sampling approaches to pursue.

(1) For steady-state testing, formalization of existing raw gaseous sampling procedures together with split-then-dilute particulate sampling, with a separate smoke opacity test cycle

(2) For non-steady-state testing, developing and demonstrating fractional sampling techniques which offer the potential for dilute sampling of gaseous and particulate emissions and in-line smoke opacity monitoring

Formalization of existing steady-state gaseous emissions test procedures should be relatively uncomplicated. Steady-state procedures presently used by the industry were drafted for the AAR in 1989 based on proven EPA procedures and techniques that were originally established for steady-state certification testing of raw gaseous emissions from heavy-duty diesel engines. [4] In addition, the draft AAR procedure [10] was intended to parallel forthcoming ISO 8178 procedures. [7,8] However, the draft AAR procedures were written for laboratory engine testing, and did not include smoke opacity measurement procedures. The AAR procedure would require some modifications to meet all of the established criteria for regulatory purposes. Specifically, modifications would have to include provisions for testing in-use locomotives and specify a smoke test procedure; however, further development of the AAR test procedure may be superfluous given the soon to be completed ISO 8178 procedures. If steady-state emissions testing is deemed sufficient, ISO 8178 <u>may</u> suffice. Recall that ISO 8178 (to date) remains under development, and should be reviewed in detail and demonstrated for use on both laboratory engines and in-use locomotives prior to blanket acceptance, or committing to further development of other procedure(s).

If non-steady-state testing is required, development of fractional sampling techniques appears to have the most promise. From a conceptual standpoint, and based on limited experience from Caterpillar and Mitsubishi, fractional sampling may accommodate emissions testing of locomotives operating over non-steady-state conditions, including step changes or cyclic (transient) operation. The first steps toward accepting this sampling approach would be to design, fabricate, and demonstrate a fractional sampling system on a full sized locomotive engine. Steady-state test result correlation of gaseous, particulate, and smoke emissions with existing test procedures would provide the first stage of authentication. Unfortunately, there are no comparative means for validating results of non-steady-state (e.g., step-change and/or transient) testing with that prototype system.

For both steady-state and non-steady-state testing, regardless of the sampling system used, certain key issues remain. For example, demonstrating that a representative sample of the exhaust is available for analyses can be achieved using techniques outlined in *Section III.F* of this report. Of equal significance is that the NO_x correction factor for combustion air temperature and humidity, that appears in Parts 86 and 89 of the CFR and also used in ISO 8178, has not been proven applicable with locomotive engines. SwRI's experience with this correction factor in locomotive field test applications has been that the correction is often in excess of 10 percent. The applicability of any proposed NO_x correction factor should be considered during the rulemaking process.

V. REFERENCES

1. SAE Recommended Practice J215 "Continuous Hydrocarbon Analysis of Diesel Emissions" last revised June 1988.

2. SAE Recommended Practice J254 "Instrumentation and Techniques for Exhaust Gas Emissions Measurement," last revised August 1984.

3. SAE Recommended Practice J177 "Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust," last revised April 1982.

4. 40 CFR Part 86 - Subpart D "Emission Regulations for New Gasoline-Fueled and Diesel Heavy-Duty Engines: Gaseous Test Procedure."

5. 40 CFR Part 86 - Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedure."

6. 40 CFR Part 89 - Subpart D "Control of Emission from New and In-Use Nonroad Compression-Ignition Engines at or Above 50 Horsepower -- Draft."

7. ISO 8178 "RIC Engines - Exhaust Emission Measurement - Part 1: Test Bed Measurement of Gaseous and Particulates."

8. ISO 8178 "RIC Engines - Exhaust Emission Measurement - Part 2: At Site Measurement of Gaseous and Particulates."

9. UN-ECE Regulation No. 49, "Uniform Provisions Concerning the Approval of Compression Ignition Engines and Vehicles With Regard to the Emissions of Pollutants by the Engine" (1991).

10. "Draft Recommended Procedure for Measurement of Locomotive Engine Emissions," prepared by SwRI for the Association of American Railroads (September 1990).

11. International Union of Railways - Office of Research and Experiments (ORE), "Question S 1015P: Acceptance Testing of Diesel Engines -- Report Number 1 - Atmospheric Pollution Caused by Exhaust Fumes" (October 1991).

12. Smith, L.R., et al, "Analytical Procedures for Characterizing Unregulated Emissions from Vehicles Using Middle-Distillate Fuels," EPA Interim Report No. EPA-600/2-80-068, (April 1980).

13. Smith, L.R., "Characterization of Exhaust Emissions from Alcohol-Fueled Vehicles," SwRI Final Report No. 03-7670, Coordinating Research Council Report CAPE-30-81 (May 1985).

14. SAE Recommended Practice J1936 "Chemical Methods for the Measurement of Nonregulated Diesel Emissions," approved October 1990.

15. SAE Recommended Practice J1151 "Methane Measurement Using Gas Chromatography."

16. Title 40, U.S. Code of Federal Regulations, Part 86, Subpart I - Emission Regulations for New Diesel Heavy-Duty Engines; Smoke Exhaust Test Procedure.

17. California Code of Regulations, Title 13, §2180-2187, CARB "Snap-Idle" Test (November 1990).

18. UN-ECE Regulation No. 24 "The Approval of CI Engines with Regard to the Emission of Visible Pollutants." (April 1986)

19. ISO/TC22/SC5 Doc. N650 "Apparatus for the Measurement of the Opacity and for the Determination of the Light Absorption Coefficient of Exhaust Gas From Internal Combustion Engines" (March 1992).

20. ISO 8178-3 "Smoke Measurement" -- Reciprocating internal combustion engines - Measurement of Exhaust Emission - Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions.

21. SAE Information Report J255a "Diesel Engine Smoke Measurement," last revised August 1978.

22. <u>Alternative Fuels Field Testing Guidelines</u>, Volume I, "Planning and Analysis," --Draft--, AAR Research and Test Department, (June 1983).

23. <u>Alternative Fuels Field Testing Guidelines</u>, Volume I, "Field Procedures," --Draft--, AAR Research and Test Department, (June 1983).

24. SAE Recommended Practice J1003 "Diesel Engine Emission Measurement Procedure," last revised June 1990.

25. SAE Recommended Practice J244 "Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines," last revised June 1983.

26. SAE Recommended Practice J1349 "Engine Power Test Code - Spark Ignition and Compression Ignition - Net Power Rating," last revised June 1990.

27. SAE Recommended Practice J1243 "Diesel Emission Production Audit Test Procedure," last revised May 1988.

28. SAE Recommended Practice J35 "Diesel Smoke Measurement Procedure," last revised September 1988.

29. SAE Recommended Practice J1151 "Methane Measurement Using Gas Chromatography, " last revised October 1988.

30. "Evaluation of Emission Controls for Locomotives, Technology Screening Report - Preliminary Draft," prepared by EF&EE for the California Air Resources Board (January 1992).

31. Chan, L.M., et al, "Evaluation and Application of a Portable Tailpipe Emissions Measurement Apparatus," SAE Paper No. 921647.

32. MacDonald, J.S., et al., "Experimental Measurements of the Independent Effects of Dilution Ratio and Filter Temperature on Diesel Exhaust Particulate Samples," SAE Paper No. 800185 (February 1980).

33. SAE Information Report J1515 "Impact of Alternative Fuels on Engine Test and Reporting Procedures," approved March 1988.

34. D.B. Kittelson and J.H. Johnson, "An Examination of the Sources of Variability in Particle Emission Measurements by the Transient Test Method for Heavy-Duty Diesel Engines," Phase I Final Report to the Engine Manufacturers Association Calibration Task Force and the Coordinating Research Council Smoke and Particulate Panel (September 25, 1990).

35. EPA Report No 460/3-83-009 "Calculation of Emissions and Fuel Economy When Using Alternative Fuels" (1983).

36. N. Hirakouchi, et al., "Measurement of Diesel Exhaust Emissions with Mini-Dilution Tunnel," SAE Paper No. 890181 (March 1989).

APPENDICES

Appendix A. Task 1.1 Report - Evaluation Criteria.

Appendix B. Two EPA-Supplied Candidate Mixing and Fractional Sampling Procedures.

Appendix C. General Motors Research Laboratories Response to Questionnaire.

Appendix D. South Coast Air Quality Management District (SCAQMD) Rule 401.

Appendix E. California Air Resources Board (CARB) Rule 41701.

APPENDIX A

TASK 1.1 FINAL REPORT - EVALUATION CRITERIA

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Contract Title:	Testing and Analytical Support for Regulation of Motor Vehicles, Engines, Fuels and Additives. Contract 68-C2-0144 (SwRI Project 08-5374)
Assignment Title:	Emissions Measurement -- Locomotives.
Task 1.1 Report:	Criteria For Evaluating Potential Locomotive Exhaust Sampling Procedures

I. INTRODUCTION

Criteria have been compiled to evaluate candidate exhaust sampling procedures and systems capable of certification level locomotive emissions measurement. Evaluation criteria were developed to qualitatively address both the potential accuracy of a candidate sampling procedure and the applicability of a given procedure to one or more of the potential operational scenarios being considered for locomotive engine testing. Discriminating elements have been assigned to many criteria, in the form of brief discussions, for purposes of criterion weighting.

Note that it is assumed that locomotive engines are defined as the prime mover used for motive power in a locomotive. These engines are generally greater than 1000 hp. A locomotive is defined as a self-propelled piece of on-track railroad equipment as distinguishable from equipment designed for operation both on-track, and on-highway.

II. OBJECTIVE

The purpose of Task 1.1 of Work Assignment 0-1 was to develop criteria for use in identifying and evaluating potential exhaust emission test procedures and measurement systems applicable to locomotive or locomotive engine testing. An analytical evaluation of candidate procedures and measurement systems will subsequently be performed using the criteria established in this Task. Based on the outcome of those evaluations, a test plan will be prepared to further develop and verify up to two of the preferred emission test procedures or systems.

Suitability of measurement systems and sampling procedures for use with diesel as well as alternate fuels (e.g. "clean" diesel, bio-diesel (or mixtures thereof), natural gas, liquefied petroleum gas, alcohols (e.g. ethanol and methanol), or combinations of these fuels) was considered while drafting these criteria. Analytical procedures and sampling systems appropriate for testing various fuels under various operating schemes shall be identified and evaluated using these criteria in the future.

Implementation of sampling systems and procedures will be limited to the measurement of gaseous (hydrocarbons, carbon monoxide, carbon dioxide, oxides of nitrogen, alcohols, and aldehydes), particulate, and smoke emissions from a locomotive or locomotive engine. In conjunction with emission measurements, engine operational data (power, fuel rate, etc.) are required to report emission results in brake specific terms. Evaluation criteria may be used to identify procedures and sampling systems which ideally permit accurate, simultaneous measurement of all test parameters.

III. LOCOMOTIVE OPERATIONAL SCENARIOS

The three locomotive or locomotive engine operational scenarios under consideration while developing these evaluation criteria were as follows:

[1] Cyclic Engine Operation

This procedure involves operating the locomotive or locomotive engine over a prescribed sequence of throttle notch positions while a single composite exhaust gas and ~~particulate~~ sample is collected. Exhaust smoke is measured continuously to determine the maximum opacity value during emissions testing.

[2] Non-Steady-State Operation at Each Throttle Notch Position

Measurement of exhaust emissions is initiated when the throttle is moved from one notch position to another, and continues for a specified period of time. A supplemental measurement could be performed following a prescribed stabilization period. The stabilization time may not necessarily be the same for each throttle notch position tested.

[3] Steady-State Engine Operation

Gaseous and particulate exhaust emission measurements are performed at each throttle notch position. Also, smoke opacity will be measured during both steady-state operation in each throttle notch as well as during the relatively short transitions as the power level of the engine is increased from one notch position to another.

IV. METHOD OF DETERMINING APPROPRIATE EVALUATION CRITERIA

Due to procedural and systemic variability from one test system to the next, it is first necessary to categorize a given candidate sampling component according to its piecewise applicability within a total system, before arriving at suitable evaluation criteria. An instrument designed to measure NO_X, for example, may not be judged among devices meant for particulate sampling, and so on. As a result of these differences, logical subgroups of criteria have been formed to evaluate subsystems of components and subsets of procedures, and how they relate to total systems and comprehensive procedures.

A checklist (see Table 1) characterizes the completeness of a candidate system with regard to locomotive emissions measurement potential. Responses to inquiries posed in Table 1 could be provided by the manufacturer, or determined using available literature. Affirmative responses to inquiries posed in Table 1 reflect the need to include the corresponding Groups of evaluation criteria (see §V. Evaluation

Criteria) in the judgement of that candidate procedure, system, or component. A comprehensive testing package is envisioned which, when assessed using the checklist given in Table 1, shall have satisfied as many as possible of the required elements and contain compatible components. Such an ideal composite system would consist of various candidate components or procedures which, when viewed separately, may not provide a complete "turn-key" system, but in combination, form a comprehensive locomotive emissions testing package.

TABLE 1. CHECKLIST FOR DETERMINING APPLICABLE CRITERIA GROUPS

GROUP	INQUIRY	Y	N
A	Does the sampling system measure engine operating parameters?		
B	Does the design allow for timely particulate matter measurement?		
C	Does the design allow for timely gaseous emissions measurement?		
D	Does the design allow for timely smoke measurement?		
E	Does design allow for timely unregulated emissions measurement?		
F	Is simultaneous emissions measurement supported?		
G	Is steady-state testing supported?		
H	Are step-change tests (i.e. transient range adjustments) supported?		
I	Are cycle tests (i.e. rapid range & PM-filter changes) supported?		
J	Can all alternate fuels be tested without system modifications?		
K	Is calibration traceability provided with candidate system?		
L	Are all necessary components supplied with the candidate system?		
M	Can all candidate systems be serviced and calibrated by end user?		
N	Are there added provisions to ensure data completeness?		
O	Can computer software (included/required) be user customized?		

V. EVALUATION CRITERIA

Suitable criteria have been compiled for determining one component's merit relative to others designed to perform a similar emissions testing task. Each subgroup of criteria (see A through O below), which may be used to determine a component's applicability within a comprehensive emissions sampling procedure, parallels an inquiry from Table 1. System compatibility, however, requires more than functional worthiness for each of its components. Interaction between components may be restricted by numerous causes; for example, computer software limitations, ease of operating a fastener on a particulate filter holder, or a range of items between these two in complexity.

Cost of each component, or projected cost to implement a candidate procedure are considered non-technical evaluation criteria; and as such, should be considered along with each of the technical evaluation criteria. Documentation is expected to vary from candidate to candidate, but should be adequate to instruct an operator as to the proper usage of the device.

When not intuitively obvious, a brief discussion follows each draft Evaluation Criterion. These brief discussions serve to further discriminate between potential candidates and provide some rationale for including the associated criteria. The criteria are not presented in order of importance relative to one another.

A. ENGINE OPERATING PARAMETER MEASUREMENT

A1. Are power, fuel rate, and air flow measurements accommodated by the candidate procedure, system, or component?

Some acceptable sampling systems depend on knowing these engine operational parameters; while others have means of avoiding the need to measure them. (e.g. MTU system assumes a BSFC and assumes a volumetric efficiency to compute exhaust mass flow. Such assumptions are not expected to prove sufficient for certification level emissions testing.)

A2. If power measurement is needed, does a candidate system provide for it?

Main alternator power measurement requires a calibrated shunt.
Does procedure correct alternator electrical power to flywheel?
Can alternator efficiency values be verified?
Will accessory power requirements be monitored?
For example: Air compressor, radiator cooling fans, load grid cooling fans, inertial air filter blower, etc.
All accessory power requirements vary as a function of ambient temperature and barometric pressure.

A3. During steady-state testing, is a standard stabilization time (if any) or scheme used for all locomotive operating notches?

A standardized amount of stabilization time may not be feasible for emissions testing of locomotives. Every engine, at any given notch position, under varied ambient conditions, has the potential to stabilize more quickly or more slowly than any other engine. Alternatively, a rate of change of some engine or emissions parameter could be used as the focus for equilibrium determination.

A4. Does the procedure control or monitor fuel temperature?

Coupled to stabilization time and total power output, fuel temperature is known to affect engine power. Alternatively fueled locomotives would require control systems capable of discerning between fuel types, and a candidate procedure should be flexible enough to allow for such cases.

A5. If fuel mass-flow measurement is needed, by what means can this be completed in an accurate manner?

Fuel flow is needed for computing BSFC and, perhaps more importantly, calculating total exhaust mass flow. By adding measured intake air flow and fuel flow, the total exhaust mass flow can be determined. This parameter is needed to compute total mass of particulate and gaseous emissions from measured volumetric concentration data.

A6. Is air flow measurement provided, if needed?

The mass flow rate of fuel along with a computed air/fuel ratio may not necessarily suffice for determining total exhaust flow for certification testing. Using computed A/F ratio is simpler than measuring both fuel and air flow, but error propagation from gaseous analyzer (e.g. CO, CO_2, HC) can limit accuracy of such a technique. Dual fuels, for example, present ~~further~~ limitations due to hydrogen-to-carbon ratios, etc.

Air flow rate measurements may be made by some form of calibrated device large enough to handle peak operating situations. Laminar flow elements (LFE), for example, have flow limitations well below locomotive engine air flow rates; therefore, some other method of air flow measurement is required during high range operations. Errors associated with measuring air flow are potentially great if calibration for a selected application is not appropriate. Accurate air flow measurement over transient operations is difficult. Any form of transient measurement scheme (i.e. integrator on instrument output) will have delays and hysterisis effects which must be considered. Turn down ratio presents a significant problem with transient operating scenarios.

Devices used for measuring air flow are generally not applicable to direct measurement of exhaust because of extreme temperatures and corrosive properties of the exhaust.

A7. Does the candidate system specify which cycle (step, transient, etc.) does or does not lend itself to success where power, fuel rate, and air flow measurements are concerned?

Does an integrator scheme meet the needs of transient, or step transient operations?
Air flow rate, for example, is a physical occurrence which does not lend itself to simple measurement. Smoothing of peaks due to slow transient response, or dampened output signals from less than ideal transducers may reduce usefulness of a candidate system.

A8. What are the individual response times and range switching capabilities of each available measurement instrument?

A correlation of engine operational parameters to emissions sampling devices in transient engine operating scenarios requires defining all instrument delays as functions of engine condition. The correlation scheme should adapt to varying ambient conditions (for air flow measurement devices), fuel type (for fuel measurement devices), and engine loading methodology (for power measurement devices).

B. PARTICULATE MATTER MEASUREMENT

B1. Is the procedure or sampling system designed for full-flow dilution or a partial "split" flow of locomotive engine exhaust?

For dilution ratios ranging from 5:1 to as high as 10:1, along with expected exhaust flow rates on the order of 14,000 standard cubic feet per minute, the full-flow dilution tunnel size which would permit homogeneous sampling would be prohibitively large. Therefore, it is assumed that candidate exhaust dilution schemes be of the split, or partial flow type. Partial- or split-flow dilution schemes are more practical for locomotive particulate matter emissions measurement.

B2. Does the candidate system provide particulate measurement?

If so, what cycle(s): Steady-state? Transient? Measuring which parameter(s) of particulate test? Is it a cumulative sample over a period of time, or an instantaneous sample?

B3. Are ambient conditions considered in particulate measurements? Are any ambient corrections needed? What correction factor formulation is provided by candidate system?

B4. Is candidate particulate sampling system capable of testing multiple-stack locomotives?

Non-turbocharged locomotives often have more than one exhaust stack.

B5. Are repeat tests required, or recommended? How many? Under what varied conditions?

B6. Does the system use conventional filter techniques?

Capture of particulate matter is commonly facilitated by passing diluted exhaust through porous filter(s). All other candidate sampling methods should provide comparable capture efficiencies to those of conventional techniques.

B7. At what position, relative to the exhaust stack, are the particulate filters located?

Exhaust stack temperatures are far in excess of 125°F, and as such, mounting of any apparatus directly onto the locomotive exhaust stack (other than a splitter pipe for diverting a portion of the exhaust into a dilution tunnel) would permit conduction of heat intense enough to compromise sample system seal integrity. In addition, leak-checking under test conditions would be required. Sample integrity is the main concern (i.e. extractables decrease as temperature increases); therefore, sample probe design and position are important.

B8. Of what materials are all sample contact surfaces within the filter holder constructed?

Corrosive materials are to be avoided. Deterioration of some rubber compounds can lead to errors due to added filter weight when seals adhere or erode onto sample filters.

B9. **What are the sizes, shapes, and materials of available filter media?**

The objectives are to gather a representative particulate sample and reduce the potential errors associated with filter handling. Filter size is designed for ease of handling, but is also limited by a function of face velocity (from the tunnel through filters).

The volume of dilute sample extracted from the dilution tunnel, by way of particulate sample pumps, should be very much less than the total dilution tunnel volumetric flow (so as not to disrupt tunnel flow patterns), but large enough to obtain a representative sample. It is assumed that fluorocarbon coated glass filter media will be used. Circular filters would minimize fragmentation due to handling. Diameters on the order of 70 mm or 90 mm are generally acceptable.

B10. For systems that utilize filtration, is there any provision in the candidate design for ease of particulate filter handling? How difficult is insertion and extraction of particulate filters into and out of filter holder?

If a candidate system or procedure does not provide easy and safe access to (and egress from) the vicinity where filter holders are located, then that candidate system is disadvantaged when cycle testing or any form of sequential sampling is needed.

To install a pre-weighed, clean filter into an appropriate particulate sampling filter holder requires that the filter media can be handled without damage and that the sampling device permits rapid, unencumbered access to the filter location.

Selectable filter holders should be provided, to allow automatic switching from one filter holder to another while the engine continues to operate.

B11. What is the methodology that ensures complete mixing has occurred at the sample zone?

In turbulent flow regimes, mixing is generally accepted to occur ten (10) tunnel diameters beyond the mixing point (orifice). Other candidate mixing techniques (e.g. porous-wall diluent to exhaust introduction schemes) should demonstrate adequate mixing forward of the sample zone.

B12. Does the apparatus or procedure provide for pre- and/or post-test filter weighing facilities?

Monitoring considerations for temperature and humidity control, required for accurate (repeatable) filter weight processing, should be clearly outlined by a candidate filter handling facility design. Most filter weighing would be done at a location removed from actual testing facilities, but some candidate systems may attempt to provide a measure of filter loading directly.

> Tapered Element Oscillating Microbalance (TEOM) techniques are an example of direct filter loading measurement which could be acceptable if calibration and correlation could be verified.

B13. What is the sample probe location and configuration? Does sample probe position affect proportionality? Is the transfer tube heated? Is it effectively sealed, so as not to leak ambient air into what should be a (measured) diluted sample?

Probe location and style within the raw exhaust stack

[a] Is it a traversing probe? If so, at what linear rate and to what proximity relative to the exhaust stack wall(s)?

Any motion of the raw sample extraction pipe would have to be uniform for all stack types.

[b] Is it a pitot-tube (i.e. isokinetic sampling) type? If so, is the entry length ten (10) tube diameters downstream from the entry point to the transitional (bend) point?

Build-up of soot due to impaction would be minimized in pitot tube type probes.

[c] If is it a full stack diameter pipe with holes drilled, then do any two holes exist on the same plane parallel to exhaust flow? (The pipe must be perpendicular to exhaust flow.)

The preferred method should be shown to be similar for each exhaust stack type. Spiral hole patterns are not as preferable as pseudo-randomly spaced patterns which ensure no two holes lie on the same plane. So as not to draw soot deposits into the testing system, holes drilled near the stack wall should be avoided.

[d] What is the ratio of sample pipe diameter to stack diameter?

B14. If there are several (redundant) probes, then what is the proximity of one opening to the next? What is the ratio of sample probe diameter to dilution tunnel diameter?

B15. What is the proximity of particulate filter holder(s) to the dilution tunnel?

Direct mounting is preferred due to the limited amount of tube wall area available for particles to adhere. Temperature of filter holders would be nearly the same as tunnel.

B16. By what means is the volume of dilute sample measured? Are there corrections to the measurement?

Filter weight gain and total volume of dilute mixture passing through the filter are essential to accurate particulate measurements. If gas meters are used to measure the total diluted volume (filtered) throughout the duration of sampling exercises, then gas meter calibration is required.

B17. What is the basis for determining dilution ratio?
How can the split fraction be determined?
Will dilution ratio be determined by means of mass flow measurements?
Will dilution ratio be determined by gaseous instrument measurements?

Perhaps the most critical measurement with spit-flow dilution is determining the dilution ratio (or dilution factor). Correlating brake-specific particulate emissions, measured using a small (< 15 %) portion of the total raw exhaust mass-flow, back to full-dilution results demands knowledge of total raw exhaust flow, the fraction of exhaust split from raw stack into tunnel, and the total flow through the dilution tunnel.

Step-change and cycle tests would require rapid range changes and transducer response capable of determining near-real-time dilution ratio. Dilution factor determination would be delayed as a function of transducer response. Due to such delays, event correlation would be difficult; and dependent on instruments, and perhaps engine notch position.

If, by some means, total exhaust flow is known, then split fraction can be calculated by first (mathematically) removing dilution air from dilute exhaust mixture. Due to the potential for error associated with each step in this process, each measurement component should be calibrated to traceable standards within the assembled system.

Mass flow rate and/or volumetric flow rate of split exhaust and dilution air flow can be determined, to varying degrees of accuracy, by several schemes. Indirect methods include mass-flow and gas-concentration schemes. Mass flow meters and pressure differential transducers must be calibrated and able to withstand the environment of locomotive engine testing; furthermore, mass flow meters typically rely on a split-flow scheme of their own. Gaseous instruments must also be calibrated. Three CO_2, or perhaps NO_X analyzers (various ranges each) can measure the concentration of a gas in the raw stack, the dilution tunnel, and the background air (diluent) for use in calculating the dilution factor, without measuring total air or exhaust flows. There are corrections to be made which rely on accurate measurements of ambient conditions when using this technique.

B18. Is the transfer tube heated (from raw stack to dilution tunnel)?

To prevent water condensation and particle adhesion, the transfer tube wall temperature should be kept above 375°F. Although this is not easily done, verification should be made using thermocouples and controllers designed to maintain a specific temperature.

B19. Does the candidate system clean, filter, or dry the dilution air flow?

B20. What is the minimum time-in-mode? How long is the sampling time necessary to provide adequate particulate loading? How much is adequate particulate loading?

C. GASEOUS EMISSIONS MEASUREMENT

C1. Does the candidate system provide some form of gaseous emissions measurement? Does the candidate system or procedure address raw or dilute gaseous emissions sampling?

Gaseous emission analyzers are generally well documented components which may be applicable to locomotive emissions measurement.

* Nondispersive infrared (NDIR) analyzers to measure CO and CO_2 concentrations.
* Chemiluminescent analyzers to measure Oxides of Nitrogen (NO_X).
* Heated Flame Ionization analyzers (or perhaps an NDIR instrument) to measure hydrocarbons (HC).

Systems for evaluating locomotive engine emissions that would use a collection of such instruments could be substantially similar to gaseous emissions measurement systems used in testing Heavy-duty diesel engines for steady-state emissions. Step change and cycle tests should consider range changing capability and sample flow rates as primary areas of concern. The greatest limitation on Step-change and Cycle test scenarios would be correlating all instruments' output to a point in time when all other parameters are known to have occurred. Modal systems may provide solutions for step change and cycle testing scenarios. Alternate fuels testing and sampling through transient engine operations may necessitate modifications to systems.

C2. Should ambient conditions be considered in gaseous emission measurements? Are any ambient corrections needed?

C3. Where are analyzers (i.e. sample line length) located relative to locomotive exhaust stack(s)?

C4. Is the gaseous measurement procedure able to test multiple stack locomotives? What is the probe configuration?

C5. Can candidate system provide data correlated in real-time to other measured parameters? Cumulative? Instantaneous?

C6. Does the system require repeat tests for determining an accurate and representative sample? How many? Under what varied conditions?

C7. How is a uniform, homogeneous sample ensured by candidate system?

A probe located in the exhaust stack such that no disturbance to the particulate splitter probe occurs (or vice-versa) is advised. Heating the probe for hydrocarbon type sampling would be required. Other sample lines should also be heated to prevent condensation from forming and restricting flow. Trapping moisture by means of coil & ice traps is recommended to create dry samples for CO and CO_2. Gaseous instruments generally must be set up for tests by adjusting zero and span values at the same flow rate as used during actual emissions sampling.

C8. What is the distance (max?, min?) from locomotive exhaust stack to sampling instrumentation?

Sample line lengths should be kept to a minimum. Pump characteristics (to draw the sample) and heated line capabilities both limit the maximum distance. A standardized length of sample line is not practical due to varied testing site facilities.

C9. What does a candidate system provide or require for instrument calibrations, bottle naming, system leak checking, bag-to-instrument verification, flow rate control, etc.?

Candidate procedures or systems which provide for easy operation are preferred. Computer controlled devices are acceptable if manual verification can also be performed.

C10. Does the candidate system address the routing of vent gases from instruments? Where are such gases directed?

D. SMOKE MEASUREMENT

D1. Does the candidate system provide smoke opacity measurement?

If so, what cycle(s): Steady-state? Transient? Regulating what portion of smoke emissions? Peak opacity? Percent of time above a specified level?

D2. Should ambient conditions be considered in smoke measurements? Corrections?

D3. Which smokemeter is appropriate? Where should it (or they) be located?

D4. Is the smokemeter capable of testing multiple stack locomotives?

E. UNREGULATED EMISSIONS MEASUREMENT

E1. Does the candidate system provide measurement of unregulated emissions (for example, aldehydes, ketones, etc.)?

What cycle(s) are supported? Steady-state? Transient? Measuring what portion of emissions? Peak? Percent of time above a specified level? Cumulative?

E2. References 1 and 2 outline sample procedures. Variations of these procedures may be applicable to locomotive testing.

1. Smith, L. R. et al, "Analytical Procedures for Characterizing Unregulated Emissions From Vehicles Using Distillate Fuels." Interim Report, Contract No. 68-02-2497, United States Environmental Protection Agency, Office of Research and Development, April 1980.

2. Smith, L. R., "Characterization of Exhaust Emissions From Alcohol-Fueled Vehicles," SwRI Final Report prepared for the Coordinating Research Council, Inc., CAPE-30-81, May 1985.

E3. Are ambient conditions considered in unregulated emissions measurement? Are any corrections needed to complete the measurement process?

E4. Where is the sampling system located for unregulated emissions?

E5. Can the candidate system perform Step Change or Cycle tests?

Samples, gathered during emission tests, are expected to be analyzed upon completion of the test. Instantaneous aldehyde and alcohol data is generally not available using present unregulated emissions sampling devices. A total emission value (for a cycle, or period of steady-state time) is typical. If segmented Step or Cycle tests are to be considered, then there should be some provision in the candidate system for easy and rapid switching to an array of parallel samplers.

E6. Are repeat tests required? How many? Under what varied conditions?

F. SIMULTANEOUS MEASUREMENT OF ALL PARAMETERS

F1. Has the sample pump been sized (and located) to provide adequate flow rates to each instrument?

In the gaseous sample line connection scheme, are flow rates and pressure drops documented? Does the performance of particulate sampling interfere with or preclude sampling of other emissions? Is unregulated emissions sampling possible while all other measurements are being taken?

Comprehensive sampling systems would be required to document all fluid movement. For a sampling system to support simultaneous emissions measurement there is a consideration relating to the sample extraction method which must be considered. Due to installation variations from locomotive to locomotive, careful consideration should be given to probe placement. In cases where one stack probe obstructs another, simultaneous measurement may be compromised. In some situations, relocating probes may not be feasible. In that regard, testing a locomotive engine in a laboratory is dissimilar to testing a locomotive on track. On-track locomotive exhaust stacks can become cluttered with probes to such an extent that repeatable results become elusive.

F2. If operation of any one component precludes the use of another, then it is to be avoided.

Excessive or unusual electrical power requirements or consumption of ~~one~~ device may compromise the use of some other component. Excessive electronic noise or interference from one component may affect the response of another and thus compromise total system effectiveness.

G. STEADY-STATE TESTING SUPPORT

For the sake of completeness, this section has been included.

G1. As a minimum for consideration, a candidate sampling procedure, system, or component must be capable of performing or supporting steady-state emissions measurement tasks.

H. STEP-CHANGE TEST SUPPORT

H1. All of the criteria which apply to steady-state tests apply to step-change tests.

Due to the step-change test's reliance on some steady-state sampling, there must be that capacity within the procedure. A Step-change, however, includes transient portions when range changing may be necessary. Rapid range changing may be vital to obtain accurate, continuous data. Instruments provide useful information only when operating well within their calibration curve.

H2. If a dilution ratio controller is employed using a mass-flow or gas-concentration scheme, to what extent can transient operations be measured? What is the transient response of the process?

H3. Does adjustment of ranges occur automatically? Manually? Continuously? How much time is required to complete each range change?

H4. Can a representative sample be taken during Step-change operations?

I. CYCLE TEST SUPPORT

All of the criteria which apply to Step-change Tests apply to Cycle Tests.

I1. (Same as H3) If a dilution ratio controller is employed using a mass-flow or gas-concentration scheme, to what extent can transient operations be measured? What is the transient response of the instrument? How is calibration and verification proven in such schemes?

I2. Can a representative sample be taken during Cycle operations?

I3. Is there any provision in the candidate design for ease of particulate filter handling? Are filter holders constructed of heavy, non-corrosive materials; and yet easy to open and close quickly?

If clamps or brackets must be loosened and removed to gain access to the filter location, then time constraints must be considered along with the added danger of potential mishap.

I4. (Same as H3) Does adjustment of ranges occur automatically? Manually? What time is required to complete each range change?

J. ALTERNATE FUEL SENSITIVITY

J1. Are diesel measurement techniques compatible with alternative fuel (i.e. natural gas, CH_3OH, etc.) emissions testing? If not, what is needed?

J2. Is the raw exhaust transfer pipe or "splitter pipe" heated? How is the splitter pipe heated, and to what temperature?

Water condensation in the transfer tube must be prevented. Methanol, in particular, presents greater potential for moisture in the exhaust than diesel.

J3. Is the dependence on mass-flow devices or gas-concentration schemes for determining the dilution ratio a problem when testing any alternate fuel?

J4. Can evaporative or fugitive emissions be monitored by candidate system?

J5. Does the candidate system provide variable heat settings for sample lines?

For diesel engine testing, hydrocarbon heated lines should be kept at 375°F, NO_X lines kept above 160°F, while CO and CO_2 do not require heating. However, during methanol fuel testing, for example, methanol begins to break down at 160°F, so sample lines with variable temperature settings are preferred.

K. CALIBRATION TRACEABILITY

K1. Is calibration of mass flow meters, laminar flow meters, etc. performed internally or externally?

K2. How invasive (i.e. degree of disassembly required) are calibration procedures?

K3. What frequency interval does the manufacturer consider adequate for calibration? Is this a reasonable schedule? Too often? Not often enough?

K4. Does the candidate system or procedure provide for automatic calibration of dilution ratio devices? And if so, by what means is the automatic calibration device calibrated?

K5. How is calibration and verification proven when using a mass-flow or gas-concentration scheme to determine dilution ratio?

K6. Can traceability to reference standards for particulate filter weighing devices be established?

K7. Can calibration of volumetric flow measurement devices be performed easily?

K8. Are there provisions in the methodology to account for tunnel conditioning between one locomotive test (or fuel tested) to the next?

Emission measurements can be influenced by tunnel preconditioning.

L. NECESSARY COMPONENT SUPPLY

If there are parts that would complete the installation, or calibration, of a candidate system that do not arrive with the system, there should be consideration of how difficult it may be to acquire those parts or supplies at a test site. Basic parts which serve to interconnect components are not included in this discussion. Calibration gases, mass standards, air flow meters, and fuel flow measurement equipment are the focus.

L1. Are there consumable goods required for candidate system usage? Are they readily available? Are there safety issues related to any of the consumables?

L2. Do any of the required calibration hardware pieces NOT arrive with the candidate system? Does the equipment supplier have a reputation that ensures dependability and accuracy of calibration devices?

L3. Are there added costs and parts needed to correctly calibrate the candidate system?

L4. Are there any add-on devices necessary to perform basic testing? Calibration? Other? Can necessary add-on products be acquired in a timely manner?

M. USAGE, SERVICE, AND CALIBRATION EASE

M1. Are any safety provisions built into the procedure, system, or component that would make it more appealing? Does any part of the safety system come at an additional cost?

M2. Are the majority of components housed in one enclosure? Is there a detailed schematic of the system provided with such a device? Is there a parts list included? Warranty?

M3. Can any or all of the sample contacting surfaces within the candidate system be cleaned? Is this easily accomplished or is partial or total system disassembly required?

M4. Are subsequent system recalibrations required as a result of cleaning?

M5. What is the weight of the sampling system? How much floor space (footprint) is required for a proper installation and operation?

The size of a testing site varies from one location to the next. If portability is the objective of a give system, then disassembly and transportability are key elements to consider. Excessive size, weight, and complexity of the system as a whole is a concern; as is the portability of the largest single component.

M6. Does transporting the candidate system or component demand recalibration?

Leak checking after relocating the system should be verified. To reduce the potential for leaks, rigid connections and dependable fasteners should be incorporated.

M7. Does the device or procedure require that technicians acquire special training? How many persons are needed to accurately operate, maintain, and calibrate a candidate system?

M8. What are the electrical power requirements of the candidate system?

N. ADDED PROVISIONS FOR PARTICULATE DATA COMPLETENESS

Data completeness implies that all test results are accurate and available given the acquired data.

N1. Are secondary particulate filters needed or used in addition to primary filters? What is the distance between filters?

Filter efficiencies vary. Distance between filters should be small (less than three inches).

N2. Is there any provision for verification of the complete mixing?

A very difficult parameter to quantify is the level of stratification of particulate (or the absence of stratification) in the dilution tunnel. A procedure or component that would allow for inspection of this phenomenon would be advantageous.

N3. Are there any provisions for leak-checking the sampling system?

A system that is not capable of checking for leaks is not attractive. An automatic procedure should have provision to allow leak checking. Propane injection and recovery methods may be satisfactory for these purposes.

N4. Is there a provision for collecting additional particulate samples? How many are sufficient?

Operation of one locomotive engine for the purposes of studying emissions is costly and time consuming. An arrangement of sample probes, and sample pumps that would provide simultaneous sampling has advantages.

N5. In Step Change or Cycle tests, does the candidate system provide additional particulate samples?

O. COMPUTER SOFTWARE COMPATIBILITY

O1. If there are computer controlled systems or devices that rely on customer configurable source code, is there any provision for verification that source code is correct and designed to sound engineering practices?

Any procedure should rely on interaction between components which are, at least in part, linked to a central computer data acquisition system. There will be the need to have access to the source code; however, this is rarely allowed. Proprietary concerns are a potential problem. Systems which perform calculations not transparent to the end-user, where software cannot be explored to the source code level, are unattractive. A suspected error in a computer program that cannot be investigated would be a problem.

O2. How is the sample zone temperature maintained? Is it part of the feedback to the "dilution ratio" control loop? Manually? Can the dilution ratio be adjusted? Is there feedback or an indication of the dilution ratio during adjustment?

One of the central elements in any dilution tunnel system or operational procedure must be the maintenance of the sample zone temperature at < 125°F. Manual adjustment of a related parameter based on a thermocouple readout may be sufficient.

If sample extraction control valves, for instance, are computer controlled and based on sample zone temperature (thermocouple), then full range capability must be demonstrated.

Transient engine operating scenarios would depend greatly on the capacity of a candidate system to adjust and measure the dilution ratio in real-time. Step-change tests using integrators to determine other parameters (i.e. gaseous emissions, power, etc.) must have rapid transient responses and brief settling times where dilution ratio adjustment is concerned. Slow dilution ratio correction and measurement would result in biased data.

VI. SUMMARY

SwRI has prepared a draft report under Task 1.1 of EPA Work Assignment 0-1 "Emissions Measurement -- Locomotives" in an attempt to develop a set of criteria which can be used to evaluate candidate exhaust emissions sampling procedures and/or emissions measurement systems for use in testing locomotives and locomotive engines. This report outlines criteria for evaluating candidate locomotive emissions sampling procedures from the standpoint that comprehensive sampling systems are designed and built using individual components. Subsets of criteria addressed functional groupings and the procedures for integrating them into a comprehensive testing package.

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APPENDIX B

EPA SUPPLIED CANDIDATE MIXING AND FRACTIONAL SAMPLING PROCEDURES

CANDIDATE SYSTEMS FOR MIXING OF ENGINE EXHAUST STREAM PRIOR TO SAMPLING

General. The following constraints are applicable to both of the exhaust mixing concepts described below:

1) A mixing assembly which attaches to the engine or locomotive exhaust system at the plane that the exhaust stream normally becomes free to enter the atmosphere. At the plane of attachment of the mixing assembly to the exhaust system, leakage of any part of the exhaust stream to the atmosphere, or the reverse, is not to occur.

2) Any incremental increase in backpressure caused by the mixing system must be limited to five inches of water measured at the engine exhaust. This limit is imposed to avoid any significant impact on engine performance and emissions due to increased backpressure.

3) Inner surfaces of the mixing system; i.e., those surfaces in contact with the exhaust stream, are to be smooth to limit particulate and soot collection on the surface.

4) All transitions on the inner surfaces of the ducting must be smooth and be designed to prevent particulate deposition or dropout.

5) Cooling of the exhaust gases in the mixing chamber should only be limited to the extent necessary to prevent condensation.

Candidate system 1. A mixing assembly consisting of the following components, starting at the attachment of the mixing assembly to the engine exhaust system. First, ducting which splits the exhaust stream into two equal flow area components at the point that the locomotive or engine exhaust gases normally enter the atmosphere. It appears preferable for the split to occur along the shorter axis of a rectangular exhaust stack -- the two resulting ducts would be more nearly square than if the split was performed along the other axis. Second, ducting which smoothly bends the two streams outward away from each other then back toward each other so that the two streams can enter a mixing chamber from opposite sides of the mixing chamber (for dual exhaust locomotives, these ducts can be replaced by ducts from each exhaust stack). While in these ducts, the introduction of a degree of rotary motion into each of the streams appears to be desirable. The direction of rotation introduced into each stream should be such that the streams are rotating in opposite directions when introduced into the mixing chamber. The points of entry into the mixing chamber are to be located so as to cause the two streams to flow almost directly into each other. Mixing could be enhanced by directing the two streams so that a component of their velocity vector is opposite to that necessary for final exiting from the mixing chamber. Third, the mixing chamber or duct in which the divided exhaust stream is remixed. At the end of the mixing chamber, the exhaust is divided into multiple streams of equal flow (the exact number of streams to be determined based on total exhaust flow and the size of the dilution tunnel and CVS blower employed). One stream is routed to the dilution tunnel. Another stream is routed through the smoke meter. The remaining streams are discharged without being sampled. To avoid sampling errors, care is to be taken to ensure that the flow through each of the final discharge ducts is equal.

Candidate system 2. A mixing assembly consisting of the following components, starting at the attachment of the mixing assembly to the engine exhaust system. First, a section of ducting with increasing cross sectional area, with a final cross sectional area of between 3 and 4 times that of the cross sectional area of the engine exhaust system at its exit. Following the section of ducting with increasing cross sectional area, a section of ducting with constant cross sectional area followed by a semicircular torus to cause flow reversal of the exhaust stream. In the plane of attachment of the semicircular torus to the constant cross sectional area ducting, the area of the hole in the center of the semicircular torus is to be approximately 1/2 that of the ducting. Second, a sheet metal cone positioned within the external ducting with its point facing into the flow of exhaust stream as it exits the engine. The maximum cross sectional area of the cone is to be approximately 1/2 that of the maximum cross sectional area of the external ducting. The tip of the cone is located approximately in the plane of the external duct where the cross sectional area of the ducting has increased to 1/2 of its final maximum cross sectional area. The maximum cross sectional areas of the cone and of the external ducting are to occur in approximately the same plane. The tip of the cone is to be removed to leave a hole through which a small portion of the exhaust stream will flow. Members used to support and locate the cone within the external duct are to be configured so as to impart a rotatory swirl to the exhaust stream. Third, an exit duct which passes through the central hole of the semicircular torus, with a cross sectional area approximately equal to that of the hole, and with its entry located coaxially with the sheet metal cone. The distance between the entry of the exit duct and the end of the sheet metal cone is to be sufficient to provide a flow area for the exhaust stream equal to approximately 1.5 times the flow area of the engine exhaust system. Toward the end of the exit duct, the exhaust is divided into multiple streams of equal flow (the exact number of streams to be determined based on total exhaust flow and the size of the dilution tunnel and CVS blower employed). One stream is routed to the dilution tunnel. Another stream is routed through the smoke meter. The remaining streams are discharged without being sampled. To avoid sampling errors, care is to be taken to ensure that the flow through each of the final discharge ducts is equal.

APPENDIX C

EMD RESPONSE TO GMR PARTICULATE SYSTEM QUESTIONNAIRE

EMD Splitter Particulate Tunnel Characterization Questions

1. What type and size (diameter) of filter media was used?
   Presumed to be Dexiglas 1.750" diameter filters
2. Was there a single filter element or two, a primary and secondary?
   Single filter element
3. What was the average face velocity of the dilute exhaust at the filter sample zone?
   Unknown
4. What was the typical and maximum filter sample zone temperatures?
   Unknown
5. What were the typical weight gain of the filter(s)?
   Not obtainable
6. What was the method for determining dilution ratio? Based on % - not deflection. Used various compressed gas mixtures to obtain proper ratio.
7. What was a typical sample time at Notch 8, 5, and Idle necessary to achieve reasonable filter loading?
   Not obtainable
8. Was the system capable of measuring (quantifying) particulate during any non steady-state operation? Unknown since only steady-state operation was tried out
9. What were the target dilution ratios?
   10:1 air to CO2; 5:1 air to CO2
10. Were there any provisions to condition the dilution air? (Filters, heating, cooling, or humidity control)
    Filters, temperature controller and heater
11. Please describe the transfer tube from the exhaust to the dilution tunnel mixing area. Was the transfer tube heated? If so, to what temperature? Utilized long 350 degree F heated sample line from locomotive/engine stack to venturi
12. What was the methodology to ensure that complete mixing of the dilution air and the raw exhaust before sampling?
    Unknown
13. What was the sample probe configuration and location? Utilized standard EMD 316 seamless stainless steel probe configuration and location
14. What is the promixity of the particulate filter holder(s) to the dilution tunnel?
    Approximately two (2) feet from exit end of tunnel.

Due to manpower limitations and gaseous exhaust emissions test requirements a limited amount of time and funds were allocated to trying to adapt GMR automotive system to EMD's diesel engine/locomotive application.

EMD personnel had little success in adapting the GMR SYSTEM to locomotive particulate emissions testing. No credible procedure or results were ever obtained.

Mary Schmid 9-1-93
Mary Schmid
EMD - Emissions Analyst

Per Roger Krieger - GMR - September 2, 1993
Methodology that went along with GMR particulate tunnel is described in the attached GMR report. Due to retirements and reassignments, the expertise on using this system is no longer available; therefore, GMR cannot answer these questions directly.

APPENDIX D

SCAQMD RULE 401

(Adopted Feb. 4, 1977)(Amended Apr. 1, 1977)(Amended Aug. 4, 1978)
(Amended Sept. 7, 1979)(Amended Feb. 1, 1980)(Amended July 11, 1980)
(Amended Oct. 15, 1982)(Amended Mar. 2, 1984)(Amended Feb. 5, 1988)
(Amended April 7, 1989)

RULE 401. VISIBLE EMISSIONS

(a) Definitions

For the purpose of this rule, the following definitions shall apply:

(1) Kerosene Fuel is petroleum distillate fuel meeting diesel grade 1-D per ASTM D975-78, fuel oil grade No. 1 per ASTM D396-79, or kerosene by conventional commericial specifications.

(2) An Approved Smoke-reducing Fuel Additive is as approved by the Executive Officer.

(3) A Synthetic Engine Lubricating Oil is as approved by the Executive Officer.

(b) Requirements

(1) A person shall not discharge into the atmosphere from any single source of emission whatsoever any air contaminant for a period or periods aggregating more than three minutes in any one hour which is:

(A) As dark or darker in shade as that designated No. 1 on the Ringelmann Chart, as published by the United States Bureau of Mines; or

(B) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subparagraph (b)(1)(A) of this rule.

(2) Not withstanding the provisions of subparagraph (b)(1) of this rule, a person shall not discharge into the atmosphere from equipment for melting, heating, or holding asphalt or coal tar pitch for on-site roof construction or repair; any air contaminant for a period or periods aggregating more than three minutes in any one hour which is:

(A) As dark or darker in shade as that designated No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines; or

(B) Of such an opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subparagraph (b)(2)(A) of this rule.

(3) Notwithstanding the provisions of subparagraph (b)(1) of this rule, a person shall not discharge into the atmosphere from any diesel pile-driving hammer, operating exclusively using kerosene fuel, containing approved smoke-reducing fuel additives, as the sole fuel, and using only synthetic engine lubrication oil, or other method deemed technologically and economically feasible by the Executive Officer, any air contaminant for a period or periods aggregating more than four minutes during the driving of a single pile which is:

(A) As dark or darker in shade as that designated No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines; or

(B) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subparagraph (b)(3)(A) of this rule.

(c) Exemptions

(1) The provisions of this rule shall not apply to the following operations:

(A) Asphalt pavement heater operations;

(B) Abrasive blasting operations;

(C) The use of visible emission generating equipment in training sessions conducted by governmental agencies necessary for certifying persons to evaluate visible emissions for compliance with this rule and with the California Health and Safety Code, Section 41704 (l).

(D) Visible emissions from ships which perform emergency boiler shutdowns, tests required by governmental agencies or maneuvers for safety purposes;

(E) Agricultural operations.

APPENDIX E

CARB RULE 41701

(b) The primary responsibility for determining whether a control measure is reasonably available shall be vested in the public agency which has the primary responsibility for implementation of that control measure. The determination of reasonably available control measure by the public agency responsible for implementation shall be conclusive, unless the state board finds after public hearing that such determination will not meet the requirements of the Clean Air Act.

41651. In addition to any other statutory requirements, at the public hearing held pursuant to Section 41650, the districts included, in whole or in part, within the nonattainment area, the designated air quality planning agency, and members of the public shall have the opportunity to present oral and written evidence.

In addition, the districts and the agency shall have the right to question and solicit testimony of qualified representatives of the state board staff on the matter being considered. The state board may, by an affirmative vote of four members, place reasonable limits on the right to question and solicit testimony of qualified representatives of the state board staff.

41652. If, after the public hearing, the state board finds that the nonattainment area plan approved by the designated air quality planning agencies does not comply with the requirements of the Clean Air Act (42 U.S.C. Sec. 7401 et seq.), the state board may adopt such revisions as necessary to comply with such requirements, except as otherwise provided in Article 5.5 (commencing with Section 53098) of Chapter 1 of Part 1 of Division 2 of Title 5 of the Government Code.

Chapter 3. Emission Limitations

Article 1. General Limitations

41700. Except as otherwise provided in Section 41705, no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property.

41701. Except as otherwise provided in Section 41704, or Article 2 (commencing with Section 41800) of this chapter other than Section 41812, or Article 2 (commencing with Section 42350) of Chapter 4, no person shall discharge into the atmosphere from any source whatsoever any air contaminant, other than uncombined water vapor, for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or

(b) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subdivision (a).

41701.5. (a) Neither the state board nor any district shall impose a discharge requirement on emissions of visible smoke from diesel pile-driving hammers which is more stringent than the requirements of this section, except as provided in subdivisions (b) and (c).

(b) A district shall issue a permit to the operator of a diesel pile-driving hammer if the operator submits a completed application for a permit to the district and the district determines, on the basis of information provided in the application, that the proposed use will comply with one of the following requirements:

(1) Meets the Ringlemann 1 limit, as published by the United States Bureau of Mines, and does not exceed that limit for more than four minutes during the driving of a single pile.